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# Development of Controls for TIME-TEMPERATURE CHARACTERISTICS IN ALUMINUM WELDMENTS

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## ADMINISTRATIVE INFORMATION

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# I. SUMMARY

This report contains a summary of accomplishments during the first twelve months of an eighteen-month research program to develop methods, tooling concepts, and processes to control the time-temperature characteristics in the weld and heat affected zone, in order to improve tensile properties and reduce porosity in aluminum weldments.

The basic concept for accomplishment of these objectives is to alter the thermal pattern in the weldment during the welding process by spraying a cryogenic liquid in the vicinity of the weld puddle as it progresses along the weld seam. The location and size of the jet sprays, as well as the total heat capacity of the selected cryogenic liquid, must be adjusted to extract sufficient heat from the weldment to produce a heat balance which will simultaneously effect the required weld penetration and increase the cooling rate of the weld metal and heat affected zone; and, in addition, cause more nearly unidirectional solidification of the weld metal. With the optimum cooling rate, the tensile properties will be increased due to the fact that: (1) the heat affected zone will be narrowed, mechanically improving the yield strength; (2) the amount of coalescence of intermetallic strengtheners will be reduced, increasing both the yield and ultimate strength; and (3) the grain size will be reduced, increasing both yield and ultimate by eliminating this source of planes of weakness. Fast cooling can also reduce gross porosity by impeding agglomeration and absorption of hydrogen and other contaminant gases. Unidirectional solidification results in lower porosity ( as exemplified by the chill casting of aluminum ingots from the bottom) by allowing entrapped gases to escape from the molten surface. All of these factors which affect tensile strength and incidence of porosity are time-temperature dependent and close control is necessary to accomplish the optimum balance.

The work accomplished to date has established the soundness of the concept. Experimental work performed thus far has demonstrated in a preliminary manner that application of the cryogenic chilling concept to TIG welding (DCSP) of 5/16" and 1/2"

plates of 2014-T6 and 2219-T87 in the horizontal position has increased the tensile strength of the welds up to 14% and reduced gross porosity more than half over welds made in the same materials without cryogenic chilling.

There is little doubt that the improvement can be increased substantially by establishing optimum thermal patterns through refinement of current techniques for applying the concept and by closer control and monitoring of all variables.

At the present time, work is being directed toward modification of equipment and instrumentation for the required control and toward variation of heat input and extraction techniques to establish optimum time-temperature relationships.

It is expected that with adequate support during the next six months, sufficient experimental work can be completed to establish a set of optimum parameters for producing thermal patterns for weldments of each plate material which will conclusively demonstrate the ability of the concept to effect sufficient increases in tensile strength and reduction of porosity to warrant its use as a fabrication technique for aluminum components of high performance aerospace vehicles. The preliminary work on heat input and heat extraction will be refined by adjusting pertinent factors such as welding current and welding speed; location, size and number of cryogenic liquid jets. Application of control methods such as the use of infrared radiometers to monitor thermal patterns, and chilling from the front side of the weldment are contemplated.

## II. PROGRAM OBJECTIVES

The objective of this program is to develop methods, tooling concepts, and processes to control the time-temperature characteristics in the weld and heat affected zone, in order to improve tensile properties and reduce porosity in aluminum weldments.

The need for this work has been brought about by the increasing requirement for higher strength-weight ratio and for greater reliability of weldments in aerospace vehicles, in particular the aluminum components for the Saturn V. These weldments have had a high incidence of porosity. Improved joint efficiencies are, of course, extremely desirable to meet the stringent design requirements.

A secondary objective of this program is to advance the state-of-the-art by developing control methods which will aid the welder in consistently producing better welds in all materials.

# III. TECHNICAL APPRCACH

## A. General

Shortening the time-temperature cycle through the critical ranges (solidification and overaging) improves the properties of aluminum alloys in general and copper bearing aluminum alloys in particular, and can be extended to apply to weldments in this material. The concept employed in this program for accomplishing the shortened cycle consists of impingement of a cryogenic liquid on the weldment during welding, and balancing heat input and heat extraction to produce thermal patterns which will result in improved weld properties.

## B. Effect of Increased Quench Rate

The copper bearing heat treatable aluminum alloys are strengthened by controlled precipitation of intermetallic compounds from the solid solution by aging. These precipitates must be finely divided and uniformly dispersed in order to accomplish strengthening. This condition is attained by a sensitive time-temperature relationship. Unless the proper relationship is maintained throughout all stages of fabrication, a soft matrix and/or brittle planes of weakness will result. Welding produces an adverse time-temperature history in that the high temperatures can produce coalescence of grain refining and strengthening elements; and, slow cooling produces overaging. Slow cooling near the melting point also produces excessively large grain growth which can result in additional loss of strength by forming planes of weakness.

Also, unless conditions are such that gases can escape through the molten liquid, slow cooling through the melting range can result in gross porosity (usually lineal), while fast cooling may produce fine scattered porosity which may not be detrimental.

## C. Effect of Unidirectional Solidification

It has long been the practice in aluminum casting to reduce gross porosity by effecting chilling in such a manner that the casting solidified from the bottom up and as nearly unidirectionally as possible.

Application of this practice to welding should also result in reduced porosity in aluminum weldments. It is, therefore, expected that proper application of chilling by means of cryogenic liquids, with or without the use of auxiliary heat sources, will reduce porosity in aluminum weldments.

## D. Chill Bars vs Cryogenic Spray Chilling

The use of chill bars is standard practice to achieve quenching during welding. While this method is perhaps adequate for welds in non-critical structure, it has three distinct disadvantages: (1) non-uniform contact between the chill bars and the work piece can cause erratic chilling with resultant hot and cold spots along the length of the weld; (2) the degree of chilling is not easily adjustable to the variety of materials, thicknesses, configurations, etc; and (3) "hard" tooling cannot always be used.

Some efforts to control weld chilling by selection of special chill bar materials, such as titanium, and insulator type materials, have indicated some promise in overcoming erratic chilling but are subject to the other limitations and produce only a limited degree of heat extraction.

The concept currently being utilized for this program is to produce chilling by impingement of a cryogenic liquid on the weldment during welding. This method appears to hold promise for overcoming the major disadvantages of "hard" tooling for chilling, and it is expected that by properly selecting the cryogenic liquid and setup for applying it during welding, the required increase in chill rate can be achieved.

# IV. PROGRAM PLAN AND SCHEDULE

The original program was divided into two phases: a four-month phase for literature and industry survey, and a fourteen-month experimental phase. The purpose of the first phase was to determine the state-of-the-art to avoid duplication of effort and to obtain any information that might be useful in the program. The second phase included all of the experimental work, and was planned to consist of two principal steps. The first was to establish realistic thermal patterns designed to improve the weld properties. The second step was to devise and test various means of providing the time-temperature controls required to attain maximum increase in tensile strength and decrease in porosity. Welding studies were to include two plate thicknesses, 5/16" and 1/2", in each of two aluminum alloys - 2014-T6 and 2219-T87. Welding was to be performed in the horizontal position by the semi-automatic TIG process, using direct current straight polarity, on square butt joint preparation with 2319 filler wire, if required.

Table I shows an outline of the experimental program, modified from the original plan to include evaluation of infrared radiation thermometers for application to the program.

Table II shows the program schedule. The following pages contain a summary of work accomplished to date, and discussions of present and future work.

TABLE I
PHASE II - PROGRAM PLAN

| Work Objectives | Operations | Samples (or Items) | Tests |
|---|---|---|---|
| A. Preliminary Experimental Work | | | |
| 1. Experimental Set-up | | | |
| a. Materials | | | |
| 1) Aluminum plates | Procure, cut, clean | 264 pcs. 6" x 48" | Visual |
| 2) Welding wire and supplies | Procure | 20 lbs. ea. 3/64" and 1/16" dia. | None |
| 3) Coolants | Select, procure | liquid $CO_2$, $N_2$, A, He | None |
| b. Equipment | | | |
| 1) Welding and fixturing | Design, fabricate, assemble | Brackets, frames, electrical | Operational |
| 2) Cooling and heating | " " " | Jets, brackets, lines, controls | " |
| 3) Accessories | " " " | Mounting brackets, electrical | " |
| c. Instrumentation | | | |
| 1) Welding current monitors | Select, install, evaluate | Voltmeter, ammeter, recorder | Operational |
| 2) Travel speed monitor | " " " | Tachometer, recorder | " |
| 3) Temperature monitors | " " " | Thermocouples, radiometers, recorders | " |
| 2. Evaluation of Infrared Radiation Thermometers | | | |
| a. General characteristics<br>Single spot, scanning | Select, obtain, install, evaluate | 10 - 12" x 48" weldments<br>50 - 6" x 12" bead-on-plate | Thermal Analysis<br>" " |
| b. Applicability<br>Emissivity, arc interference | Modify, supplement, evaluate | 10 - 12" x 48" weldments<br>50 - 6" x 48" bead-on-plate | " "<br>" " |
| c. Adaptation<br>Mechanical, calibration | Design, fabricate, install, evaluate | 20 - 12" x 48" weldments<br>100 - 6" x 12" bead-on-plate | " "<br>" " |
| 3. Reference Weldment Characteristics | | | |
| a. 5/16" 2014-T6 square butt joints | Weld, monitor, test | 6 - 12" x 48" weldments | X-Ray, macro, micro, 3 tensiles, hardness |
| b. 1/2" " " " " | " " " | 6 - " " | |
| c. 5/16" 2219-T87 " " " | " " " | 6 - " " | " " " |
| d. 1/2" " " " " | " " " | 6 - " " | " " " |
| 4. Preliminary Chilled Weldment Characteristics | | | |
| a. Coolants | | | |
| 1) Liquid carbon dioxide | Weld, monitor, test | 6 - 6" x 12" bead-on-plate | Macro, micro, hardness |
| 2) Liquid nitrogen | " " " | 6 - " " | " " " |
| 3) Liquid argon | " " " | 6 - " " | " " " |
| b. Cooling Method | | | |
| 1) Jet spray types and orifice diameters | Select, procure, install, test | 12 - 6" x 12" bead-on-plate | Macro, micro, hardness |
| 2) Jet spray positioners | Fabricate, install, test | 12 - 6" x 12" " | " " " |
| 3) Weld backing materials and devices | Select, procure, install, test | 12 - 6" x 12" "<br>6 - 12" x 48" weldments | " " "<br>X-Ray, macro, micro, 3 tensiles, hardness |

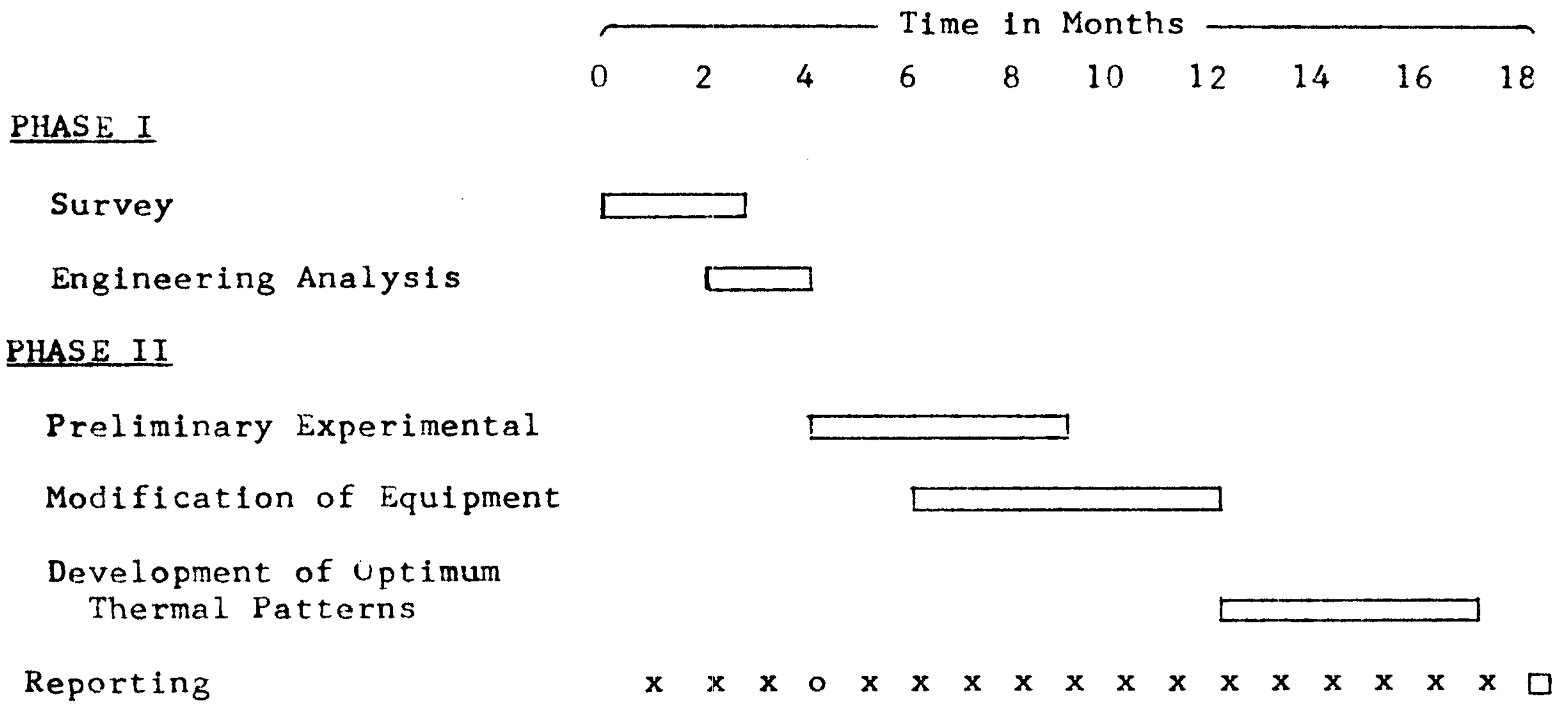
Phase II - Program Plan, Cont'd

| Work Objectives | Operations | Samples (or Items) | Tests |
|---|---|---|---|
| B. Modification of Equipment | | | |
| 1. Welding equipment<br>Torch positioners, hold-down tooling, power supply | Select, fabricate or procure install, evaluate | 4 - 12" x 48" weldments | Operational |
| 2. Chilling equipment<br>Jets, positioners, back-up materials | Select, fabricate or procure install, evaluate | 4 - 12" x 48" weldments | Operational |
| 3. Auxiliary heating equipment<br>Auxiliary torches, quartz lamp | Select, fabricate or procure install, evaluate | 4 - 12" x 48" weldments | Operational |
| 4. Instrumentation<br>Voltmeters, ammeters tachometers, thermocouples, radiometers, resistance thermometers, fuses | Select, fabricate or procure, install, evaluate | 20 - 12" x 48" weldments<br>60 - 6" x 12" bead-on-plate | Operational, analytical<br>" " |
| C. Development of Optimum Thermal Patterns | | | |
| 1. 5/16" 2014-T6 Plate<br>Variation of heat input and chilling patterns | Set-up, weld, monitor, test, analyze | 10 - 12" x 48" weldments | Thermal analysis, X-Ray, macrosection, microsection, Tensile |
| 2. 1/2" 2014-T6 Plate<br>Variation of heat input and chilling patterns | Set-up, weld, monitor, test, analyze | 10 - 12" x 48" weldments | Thermal analysis, X-Ray, macrosection, microsection, Tensile |
| 3. 5/16" 2219-T87 Plate<br>Variation of heat input and chilling patterns | Set-up, weld, monitor, test, analyze | 10 - 12" x 48" weldments | Thermal analysis, X-Ray macrosection, microsection, Tensile |
| 4. 1/2" 2219-T87 Plate<br>Variation of heat input and chilling patterns | Set-up, weld, monitor, test, analyze | 10 - 12" x 48" weldments | Thermal analysis, X-Ray macrosection, microsection, Tensile |
| | | Total samples:<br>106 - 12" x 48" weldments<br>214 - 6" x 12" bead-on-plate | Total Tests:<br>Thermal analysis - 320<br>X-Ray - 160<br>Macro - 150<br>Micro - 75<br>Tensile - 450<br>Hardness - 75 |

TABLE II

PROGRAM SCHEDULE

(Revised October 1965)




x = Monthly reports

o = Phase report

□ = Final report

# V. WORK PREVIOUSLY REPORTED

## A. Summary

The survey of literature and industry was completed in the scheduled period of four months. It was determined that this program does not duplicate any previous work, and that the approach of supercooling had merit. Some theoretical background in heat transfer applicable to welding (unsteady state with a moving single point heat source) was obtained.

Results of preliminary experimental work on alteration of thermal patterns in aluminum weldments by application of the concept of cryogenic jet spray chilling have demonstrated that the concept is sound. Tensile strength of weld joints in 2014-T6 plate was increased from 5 to 14 percent by application of the concept. Examination of X-rays and fractures indicate that porosity can be reduced by a factor of two over unchilled welds.

## B. Literature and Industrial Survey

The purpose of the survey was to obtain information which might be helpful in the performance of this program, by avoiding duplication of effort and/or by supplementing the original program concept.

Current abstract bulletins published by the National Aeronautics and Space Administration (STAR) and by the Defense Documentation Center (TAB) were checked for reports of work pertinent to fusion welding of aluminum, and significant reports were acquired for review.

A similar survey was made of applicable technical books and periodicals, including those of the American Welding Society, the American Society for Metals and the American Institute of Mining and Metallurgical Engineers. Particular emphasis was devoted to issues of the Welding Journal published during the past ten years.

Sixty-three reports were selected for review and were classified under three general subject areas according to their principal interest to this program: (1) Time-Temperature Studies, (2) Heat Flow During Welding, and (3) General Welding Techniques.

No reported or unreported work was gound which would indicate that any part of this program is a duplication of effort. A considerable amount of information was obtained which will facilitate the experimental portion of the program, particularly that work pertaining to heat transfer analysis and specific welding techniques currently in use for fabricating aerospace structures by welding the particular materials involved.

## Organizations Contacted

Those organizations and individuals who were considered to be involved in work related to this program were contacted for personal interview or for interview by telephone. The cooperation was excellent, and in some cases special data were furnished and tours of plant facilities arranged. In general, a great deal of interest was expressed in this program.

It appears that at the present time, no specific work is in progress to develop data in addition to that already reported in the literature for development of time-temperature controls or theoretical heat flow information for welding of aluminum alloys.

However, in some work completed in 1965 by Frankford Arsenal it was determined that three significant trends were noted in the microstructure which indicate the merit of the use of super-chilling during welding of aluminum: (1) the amount of microporosity was substantially lessened, (2) the width of the zone of grain boundary melting at the interface was reduced appreciably, and (3) a finer grained cast structure was obtained. All of this work was performed on 0.090" thick 2014 and 2024 aluminum alloys. In one set of experiments, the chill bars (both top and bottom) were cooled with brine at -45$^{o}$F. In a second set, for which data has been published recently, the chill bars were cooled with liquid nitrogen. In each case, welding was performed after the parts to be welded reached a selected temperature, -30°F and -250°F, respectively. Difficulty with condensation of moisture on the parts was overcome by enclosing the part in a flexible bag containing dry argon or helium.

A large amount of work has been done and is currently in progress to improve the quality of weldments in aerospace components fabricated from aluminum. Although only a few specific studies have apparently been conducted on a laboratory basis for determining the effect of time-temperature on properties of weldments, a good many of the process controls adopted for shop welding are aimed in the direction of controlling thermal patterns.

## C. Experimental Work

### 1. General

Work which has been previously reported consisted principally of welding equipment and instrumentation setup, preliminary heat input and extraction studies, preliminary thermal pattern studies, tensile testing of welds in 2014-T6 plate, and equipment modification. Work was initiated for obtaining thermal patterns in chilled and unchilled welds in 2219-T87 plate. An evaluation of infrared radiometers for application to the program was performed, indicating that this instrumentation would be advantageous for control of thermal history in weldments.

### 2. Equipment

Existing equipment was modified for welding test panels from one side in the horizontal position by the TIG (DCSP) process. The basic equipment consists of a Miller Model 600/1200 power supply, a Miller high-frequency unit, a Berkeley-Davis side beam and carriage, an Airco TIG welding torch with a "proximity" control, an Airco wire feed system, and suitable brackets and attachments for mounting the cryogenic jet spray system and radiometers.

3. Instrumentation

As shown in the sketch on the following page (Figure 1), the instrumentation for monitoring welding process variables and thermal patterns in the weld panels consists of Weston ammeter and voltmeter, an optical tachometer, a Leeds & Northrup 12-channel temperature recorder with thermocouples, an Airco helium flowmeter, an Airco filler-wire speed regulator, a Tektronic oscilloscope, and infrared radiation thermometers.

Rapidly changing temperature and steep thermal gradients in the weld area require extremely fast and accurate continuous recording of temperatures. Results of preliminary experimental work indicate that the 12-channel Leeds and Northrup rocorder is not adequate, and procurement of a continuously recording galvanometer-type instrument is contemplated. Thermocouples do not appear to be suitable for a system using continuously monitored isotherms as the basis for control in production welding due to the attachment problem. Use of infrared radiometers is contemplated as the solution to the problem.

4. Weld Preparation

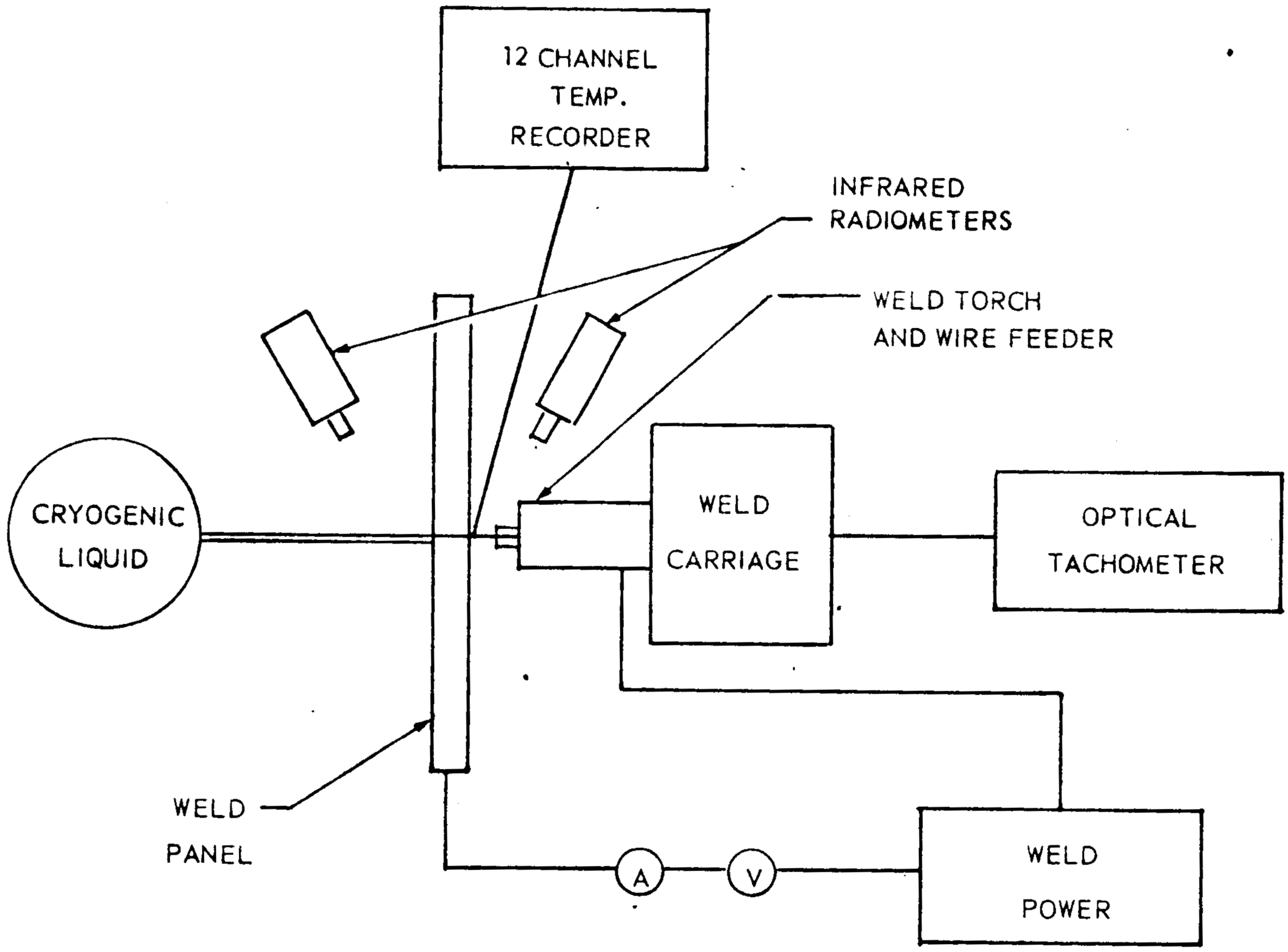
Standard procedures (including chemical etching and draw filing) for cleaning and handling the plate materials were followed. Square butt edge preparation was used for all welds.

5. Preliminary Heat Input Studies

Welds were made in 5/16" and 1/2" thick 2014-T6 and in 1/2" 2219-T87, both with and without liquid $CO_2$ chilling. Attempts were made to produce full penetration and bead contour with one pass and without the addition of filler wire, in an effort to keep the thermal history of the welds to a minimum and to eliminate addition of filler wire as another source of porosity. This was accomplished successfully for 1/2" thick 2014-T6, but resulted in a slight amount of undercut on the face side for the 5/16" thick 2014-T6 and the 1/2" thick 2219-T87. The efforts to produce satisfactory one-pass, no-filler welds will be continued in future work for development of optimum heat input.

Figure 1.

SKETCH OF EXPERIMENTAL SETUP



6. Preliminary Heat Extraction Studies

Liquid $CO_2$ was selected for the preliminary experimental work because of its relatively high heat of vaporization in conjunction with low cost and ease of handling. The liquid $CO_2$ is supplied in 250 lb. containers with suitable outlet and safety valves. Special flexible tubing and a variety of nozzles with orifice sizes from 0.008" to 0.032" were obtained for application of the $CO_2$ to the back side of the weld as illustrated in the sketch on the following page (Figure 2).

Results of initial tests indicated that chilling from the $CO_2$ would be sufficient to significantly alter the thermal pattern of the weldment as shown in the following table.

TABLE III

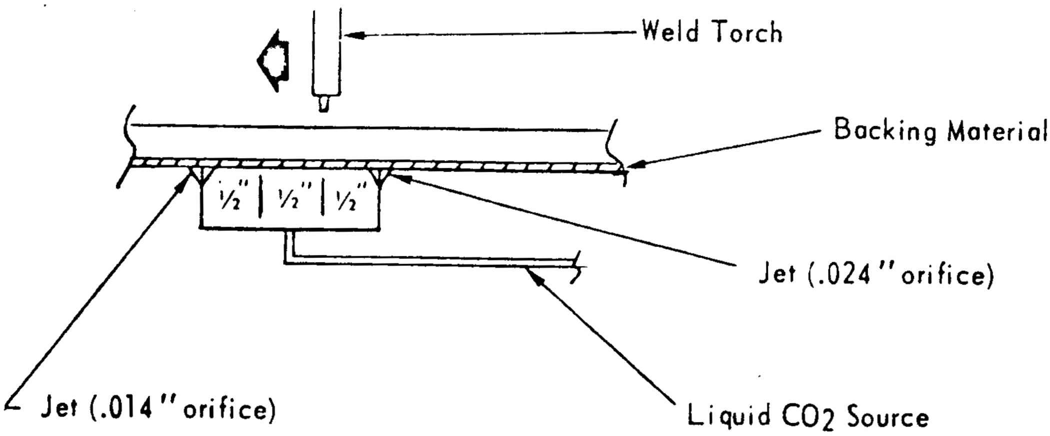
Cooling Available for Altering the Thermal Pattern of Weld Panels Chilled By Liquid $CO_2$ (Preliminary Data)

| Weld Panel | Thickness (inches) | Input (BTU/in.) | Cooling Provided by Liquid $CO_2$ (BTU/in.) | | |
|---|---|---|---|---|---|
| | | | Total Provided (50% effic) | Absorbed in Forming Bead | Available for Quenching |
| 1A1 | 5/16 | 22.2 | none | | |
| 1EC1 | 5/16 | 31.1 | 14.5 | 8.9 | 5.6 |
| 1F2 | 1/2 | 36.4 | none | | |
| 1DC3 | 1/2 | 44.1 | 16.7, | 7.7 | 9.0 |

Adhesive glass tape over non-adhesive glass tape was selected as the backing material because it is readily adaptable for the purpose. Subsequent bead-on-plate tests indicated that aluminum foil and copper foil or mesh provided greater heat transfer, and it is contemplated that further tests on these materials will be performed in future experimental work.

Figure 2.

Jet Arrangement No. 1:




Backing Material No. 1: Adhesive glass tape over non-adhesive glass tape.

7. Preliminary Thermal Patterns

Data obtained from the preliminary heat input and extraction studies were plotted in terms of thermal patterns (isotherms versus distance from welding electrode position) and time-temperature cycles for points at various distances from the weld centerline. These data are shown in Appendices I and II. From these curves it is apparent that chilling the back side of the weld significantly alters the thermal pattern. It is contemplated that future work will include adjustment of welding and chilling variables to produce even steeper thermal gradients and higher quench rates.

8. Weld Properties

The following table shows averages of tensile test results for specimens from welded panels in 5/16" and 1/2" 2014-T6 plate.

TABLE IV

Comparison of Tensile Properties of Unchiled Welds and Welds Chilled by Liquid $CO_2$ in 2014-T6 Plate (Preliminary Data)

| Specimen | Test | Tensile Properties | | |
|---|---|---|---|---|
| | | Unchilled | Chilled | Improvement |
| 5/16" Bead on | Yield (psi) | 27,900 | 30,300 | 8.6% |
| | Ultimate (psi) | 42,100 | 45,500 | 8.1% |
| | % Elongation in 2" | 5.0 | 7.0 | 40.0% |
| 1/2" Bead on | Yield (psi) | 27,500 | 31,500 | 14.5% |
| | Ultimate (psi) | 45,300 | 47,600 | 5.8% |
| | % Elongation in 2" | 5.5 | 6.0 | 9.1% |

All tests were performed at room temperature. In order to evaluate the effect of chilling on tensile properties, it was necessary to select tests for specimens which contained less than 1% porosity in the fractured area so that the effect of porosity would not mask the effect of metallurgical changes. It was further necessary to limit these specimens to comparable groups, which again narrowed the selection.

It appears that there are improvements in tensile strength ranging from approximately 5% to 14% for welds chilled by $CO_2$.

All welds contained some degree of porosity. Those made by one penetration pass without the addition of filler wire contained relatively small amounts of fine scattered porosity.

Results of preliminary X-ray examination and tensile test fracture studies indicate that chilling the back side of the weld with liquid $CO_2$ effects some reduction in gross porosity. For welds in 5/16" 2014-T6 plate, the average porosity for all specimens from the unchilled weld panel was 5%, while the average porosity for all specimens from the chilled weld panel was 2%, indicating that chilling reduced the amount of this porosity by a factor of more than two.

For specimens from the 1/2" plates, welded without the addition of filler, X-ray results and fracture studies indicated less than 1% porosity in both chilled and unchilled welds.

Two welds made by one penetration pass and one filler pass contained substantial amounts of large porosity. Of this group, the unchilled weld exhibited 60% more porosity than the chilled weld. A large amount of this porosity in the unchilled weld was lineal, while the porosity in the chilled was essentially scattered.

Gross lineal porosity appears to be associated with the addition of filler wire. The causes for fine scattered porosity have not yet been determined. In both instances, the causes must be investigated and corrected before the effect of chilling on eliminating or reducing porosity and improving weld properties can be properly evaluated.

While these results cannot be considered conclusive, and indicate the need for further refinement of general welding techniques, there appears to be sufficient evidence of improvement to warrant further development of the current concept.

## 9. Infrared Radiometer Studies

Studies were made to determine the applicability of infrared radiometry to measurement of temperatures of the weldment during the welding process. A survey was made of various types of instruments available, and three were selected for experimental study. All contained a PbS detector with germanium lenses capable of small target size and focal length from 6 to 30 inches or more. Two were fixed spot and the third was a line scanner. Results of studies indicated that infrared radiometry could be adapted to this program by making provisions for the varying emittance of the work piece and interference from the welding arc. Fixed spot radiometers are more suitable for the work in this program, as monitoring of the temperature of one or more single points for weld parameter control will be the major purpose for radiometer use. Precise information on the temperature of a single point cannot readily be obtained from a line scanning radiometer, while fixed point radiometers are ideally suited for this application and are considerably less expensive. It is contemplated that future work will include the use of infrared radiometers in the instrumentation, with eventual application as a quality control device.

## VI. CURRENT WORK

During the month of March 1966, the effort was directed toward completion of preliminary work on chilled and unchilled welds in 2219-T87 plate, and preparation for establishing optimum thermal patterns.

Welding parameters were established for producing chilled welds in 1/2" 2219-T87 using jet arrangement #3, as shown in the following sketch and Table V.

TABLE V

Welding Parameters for 2219-T87 Plate

| Panel No. | Thickness | Chill | Amps | Volts | Travel Speed |
|---|---|---|---|---|---|
| 2AC-1X | 5/16" | none | 178 | 12.1 | 7.1 ipm |
| 2AC-1 | 5/16" | Jet Arr.#2 | 178 | 12.1 | 7.1 ipm |
| 2B2-20 | 1/2" | none | 342 | 12.0 | 8.7 ipm |
| 2BC-1 | 1/2" | Jet Arr.#1 | 338 | 11.9 | 7.5 ipm |
| 2BC-2 | 1/2" | Jet Arr.#2 | 341 | 11.9 | 7.5 ipm |
| 2BC3-1 | 1/2" | Jet Arr.#3 | 335 | 12.3 | 8.3 ipm |

Results of tensile tests for weld panels 2AC-1X (5/16", unchilled), 2AC-1 (5/16", chilled), 2B2-20 (1/2", unchilled) and 2BC-3-1 (1/2", chilled) are shown in Table VI. All welds were made in a single pass without the addition of filler wire to reduce the number of variables. The weld bead for the "bead-on" (as-welded) 5/16" unchilled specimens were undercut to such an extent that failure occurred in the weld metal rather than the heat affected zone.

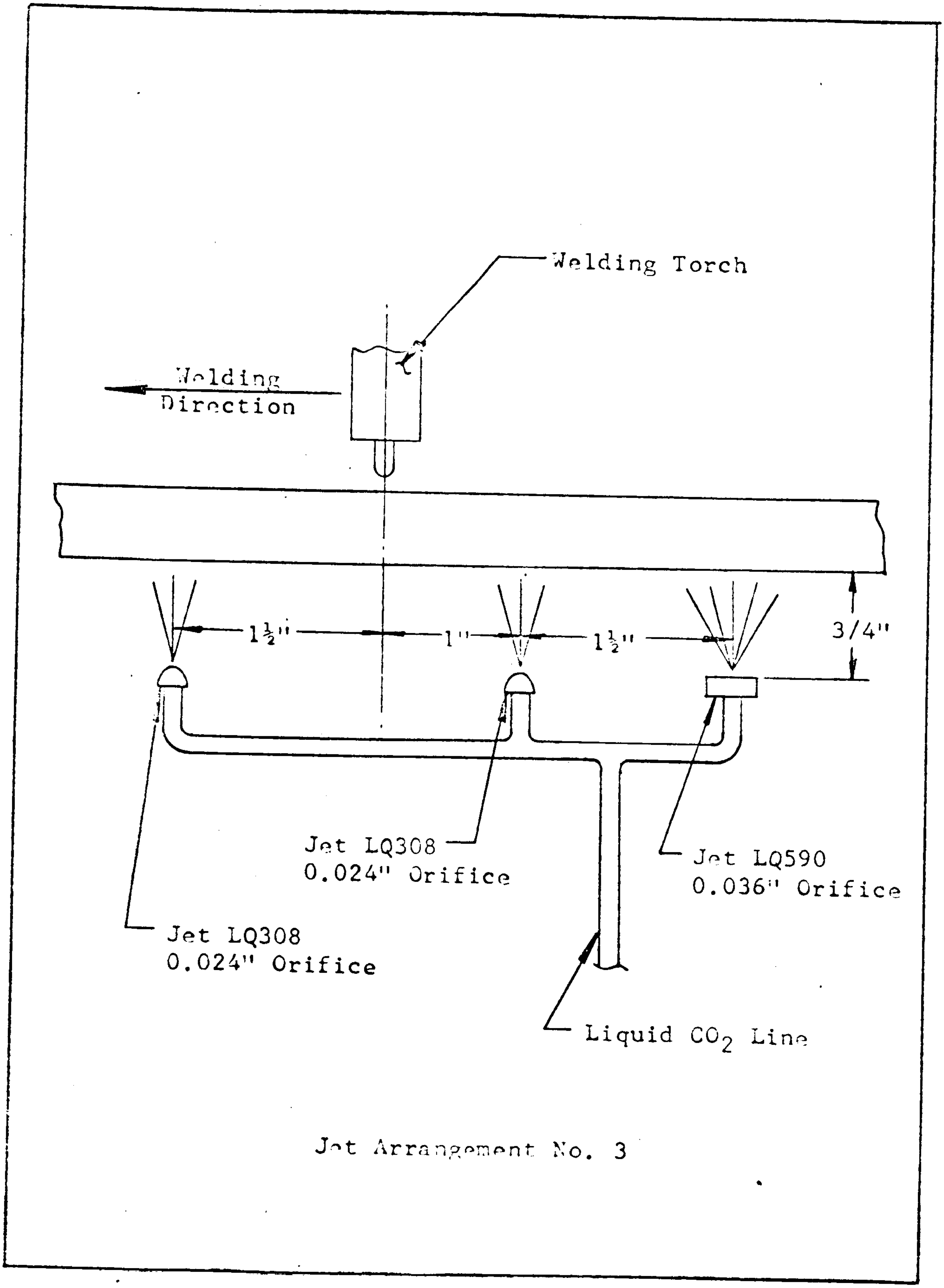

Welding Torch
Welding Direction
1½"
1"
1½"
3/4"
Jet LQ308
0.024" Orifice
Jet LQ590
0.036" Orifice
Jet LQ308
0.024" Orifice
Liquid $CO_2$ Line
Jet Arrangement No. 3

Figure 3

TABLE VI

Comparison of Tensile Properties of Unchilled Welds and Welds Chilled by Liquid $CO_2$ in 2219-T87 Plate

(Preliminary Data)

| Specimen | Test | Tensile Properties | | |
|---|---|---|---|---|
| | | Unchilled | Chilled | Improvement |
| 5/16"-Bead-on * | Yield (psi)<br>Ultimate (psi)<br>% Elong. in 2" | 18,500<br>36,000<br>4.0 | 19,300<br>37,300<br>4.0 | 4.3%<br>3.6%<br>0 |
| 5/16"-Bead-off | Yield (psi<br>Ultimate (psi)<br>% Elong. in 2" | 17,000<br>37,100<br>6.0 | 19,000<br>38,300<br>4.0 | 11.8%<br>3.2%<br>- |
| 1/2"-Bead-on | Yield (psi)<br>Ultimate (psi)<br>% Elong. in 2" | 18,000<br>38,500<br>4.0 | 20,400<br>42,000<br>6.0 | 13.3%<br>9.0%<br>50% |
| 1/2"-Bead-off | Yield (psi)<br>Ultimate (psi)<br>% Elong. in 2" | 17,600<br>36,300<br>4.0 | 18,800<br>38,000<br>5.0 | 6.8%<br>4.7%<br>25% |

*Both unchilled and chilled welds contained excessive undercut causing failure to occur in the weld metal rather than the heat affected zone.

Work was begun to minimize heat input for unchilled welds in 5/16" 2219-T87, resulting in parameters shown below for a single pass square butt weld.

TABLE VII

| Panel No. | Thickness | Chill | Amps | Volts | Travel Speed |
|---|---|---|---|---|---|
| 2AM-1 | 5/16" | None | 270 | 11.3 | 16.8 ipm |

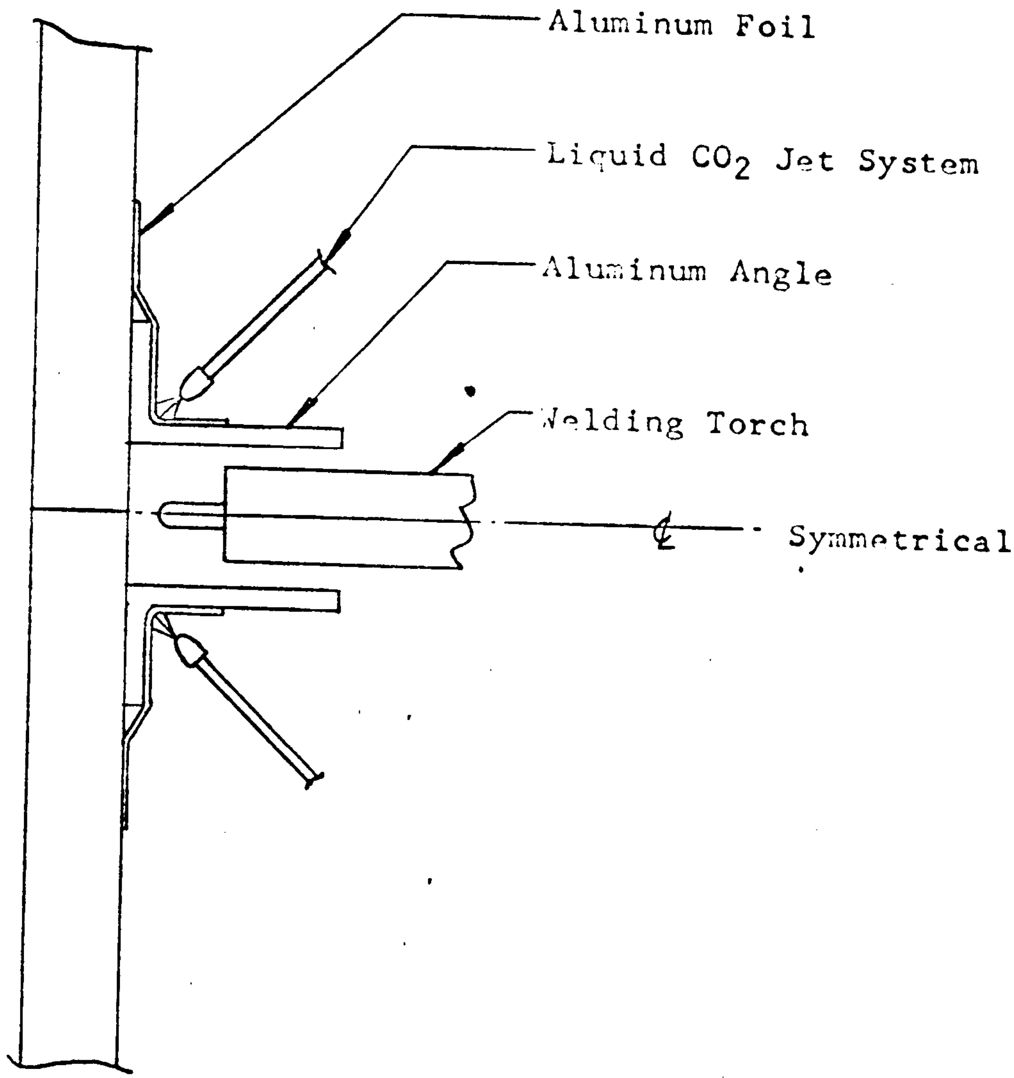
The energy input for this weld was only 34,200 joules per in./in., which is considerably below usual inputs. Although this weld has a slight amount of undercut, it is expected that this can be overcome by further refinement of welding parameters. Macro section studies and tensile tests are expected to be completed during the next report period.

Jet holders and brackets have been fabricated for use in initial trials to chill the weld from the front (torch) side. A thin aluminum angle will be attached to the plate on each side of the torch, and aluminum foil will be used as a seal to prevent $CO_2$ from leaking into the arc area. Single or multiple jet sprays will be used on each side of the torch as illustrated in the following sketch. (Figure 4)

Data Reduction and Presentation

Time-temperature plots were prepared from each weld test. To supplement the thermal history provided by the 12-point L&N recorder, special thermal runs were conducted which produced a single trace of the entire heating and cooling history for a particular distance from the weld centerline. Three distances were evaluated: 3/8", 6/8" and 1-1/4". The techniques utilized for combining these curves to provide a fairly complete thermal profile were discussed in the last progress report. Plots are shown in Figures 11 thru 23, Appendix I'. From these curves, isothermal patterns and Time-Temperature curves for points along the weld centerline will be prepared.

Efforts are in progress to obtain a relatively simple correlation for the welding variables. At the present time, it appears that no single mathematical relationship can accurately describe both the heating and cooling history for a point at a specific distance from the centerline of the torch travel. Adams' paper ("Cooling Rates and Peak Temperatures in Fusion Welding", Welding Journal, Welding Research Supplement, pp 210-215s, May 1958) concentrated primarily on peak temperature distribution, rather than describing the complete thermal cycle. However, preliminary calculations of cooling rates, based on his equation (2) were performed and a fair correlation appears




Sketch of Jet System Arrangement
for Chilling Weldments from Front Side

Figure 4

to exist, particularly in the shape of the curve, for periods up to 20 seconds (to temperatures below 500°F). Unfortunately, these equations include an efficiency factor, which cannot be readily computed, without additional work. Other assumptions which broaden the base for inaccuracies are the lack of specific data at elevated temperatures for the thermal diffusivity of the alloys (a function of specific heat, thermal conductivity and density). It is assumed that the diffusivity does not vary with temperature. This appears to be another area which should be clarified in order to more adequately define and control the welding process.

# VII. FUTURE WORK

## A. Summary

The major effort during the balance of the experimental portion of the program will be directed toward establishing optimum parameters of heat input and heat extraction to obtain time-temperature relationships for each material and each plate thickness to produce the maximum increase in tensile strength and reduction of porosity. Heat input factors will be modified to produce welds of acceptable physical dimensions with a goal of 40,000 joules/in./in. or less for unchilled welds. Heat extraction factors for chilled welds will be adjusted to produce a chill rate of as near as possible to 100°F/sec. in the range of 750°F to 500°F for any portion of the weldment, and to reduce the total time at temperature above 500°F to 10 seconds or less. It is expected that when optimum time-temperature parameters are established, the tensile strength of chilled welds will exceed the strength of unchilled welds up to 20% and that gross porosity will be reduced by at least one-half.

If adequate support is available, work will be initiated to perform the chilling operation from the front side and to monitor and control thermal patterns during the welding operation by means of infrared radiometers.

The following table shows the approximate number of samples to be welded and the tests to be conducted. This table represents a program designed in accordance with support expected to be immediately available, and should result in data of reasonable reliability which will indicate the feasibility of developing the concept for eventual process control for welding aerospace vehicles. Microhardness, microscopic analysis and detailed radiometer studies have been omitted. Techniques for chilling from the front side of the weld will be investigated in a preliminary manner, and if success is immediately indicated, this method will be used in lieu of chilling from the back side for generation of data on optimum thermal patterns.

## TABLE VII

### Estimated Number of Weld Samples and Tests Required for Development of Optimum Thermal Patterns

| Material | Thickness | Chill | Bead on Plate | 12"x48" Panels | X-ray | Macro | Tensile: Bead on | Tensile: Bead off | Thermal Analysis: B/P | Thermal Analysis: Panels |
|---|---|---|---|---|---|---|---|---|---|---|
| 2014-T6 | 5/16" | None | 10 | 2 | 2 | 4 | 6 | 6 | - | 2 |
| | | $CO_2$ | 20 | 2 | 2 | 6 | 6 | 6 | - | 2 |
| 2014-T6 | 1/2" | None | 10 | 2 | 2 | 4 | 6 | 6 | - | 2 |
| | | $CO_2$ | 20 | 2 | 2 | 6 | 6 | 6 | - | 2 |
| 2219-T87 | 5/16" | None | 10 | 2 | 2 | 4 | 6 | 6 | - | 2 |
| | | $CO_2$ | 20 | 2 | 2 | 6 | 6 | 6 | - | 2 |
| 2219-T87 | 1/2" | None | 10 | 2 | 2 | 4 | 6 | 6 | - | 2 |
| | | $CO_2$ | 20 | 2 | 2 | 6 | 6 | 6 | - | 2 |
| Backing Materials Studies | 1 Mat'l 1 Thickness | $CO_2$ | 10 | 1 | 1 | 6 | - | - | - | 2 |
| Front Side Chill Studies | 1 Mat'l 1 Thickness | $CO_2$ | 10 | 2 | 2 | 7 | 6 | 6 | - | 2 |
| Total | | | 140 | 27 | 19 | 59 | 54 | 54 | - | 20 |

For a higher degree of reliability of data and more detailed studies of improved methods of producing, monitoring and controlling thermal patterns for process specification development, experimental work and testing in addition to that shown in Table VII will be performed if adequate support is available.

B. The following paragraphs contain discussions of each major portion of the experimental work.

1. Heat Input

Welds will be made in each thickness of each material using minimal heat input (approximately 40,000 joules/in./in.) which will produce welds of acceptable penetration and bead contour. Efforts will be directed toward producing these welds in one pass without the addition of filler metal. In the event that it is not possible to produce a full bead contour without filler wire, additional welds will be made using a minimum amount of 2319 filler. Full bead contour is necessary so that failure in the heat affected zone will occur, to determine the strength of this area. A second set of specimens will be tested with the bead machined flush on both sides so that the strength of the cast structure or the weakest area of the weld can be determined.

Two 12" x 48" panels will be welded and tested for each material and thickness as shown in Table VII, with the objective of obtaining unchilled welds with optimum properties. Additional bead on plate welds will be made as required to obtain approximate parameters.

2. Heat Extraction

Optimum heat extraction studies will be conducted for welds in each material and each thickness to obtain maximum improvement in tensile strength and reduction in porosity over unchilled welds. Parameters developed in the preliminary studies will be modified by adjusting and supplementing current equipment and techniques including varying the number, size and location of jets, weld backing materials, and if necessary, use of cryogenic liquids other than liquid $CO_2$.

Two 12" x 48" panels will also be welded and tested for this portion of the work, in addition to bead-on plate welds to obtain approximate parameters.

3. Optimum Thermal Patterns

Data obtained from development of optimum heat input and extraction will be reduced to the proper form for plotting time-temperature cycle curves for critical locations on the weldment, and isothermal patterns will be drawn for each unchilled and chilled weldment which demonstrate maximum tensile strength and reduction in porosity. From these isotherms, four points will be selected on the face of the weldment for each material and each thickness. Monitoring the surface temperature of all or some of these points will be used as the basis for development of a feed back control system utilizing infrared radiometers, if sufficient support is available.

4. Chilling from Front Side of Weld

As it may be impractical in some cases to chill the back side of a production weldment by means of liquid cryogenic spray systems, initial work will be started to determine the merits of chilling from the front (torch side) using the arrangement shown in Figure 4, Section VI, or some similar arrangement. It is expected that it will be possible to effect increased cooling rates and steeper thermal gradients by this method. Anticipated problem areas include solidification direction and interference with the welding operation. However, it is expected that these problems can be overcome by optimum equipment design and jet arrangements, together with the use of liquid argon or helium, if necessary.

5. Infrared Monitoring

It appears to be impractical to monitor thermal patterns in production weldments by means of thermocouples due to the difficulty in making adequate contact with the part in critical locations. As infrared radiometers are capable of measuring temperatures with reasonable accuracy without contact, an initial investigation is contemplated for the application of this method to time-temperature control during welding, if adequate support is available. Four radiometers will be mounted on the weld carriage and focused on critical points on the front side of the weld. Two will lead the torch (one on each half of the part to be welded) to monitor effective welding heat and two will follow the torch to monitor effective chilling. A fifth radiometer will be mounted on the carriage and focused in such a manner as to monitor weld penetration. While it may not be practical to use a radiometer on the back side of a production weldment, it will provide valuable assistance in correlating proper heat balance in the weldment with the radiometers mounted on the front side. It is expected that such a system could be developed for automatically controlling thermal patterns in weldments.

Problems anticipated include variations in surface emittance of the work piece and interference from emissions from the welding arc. Possible solutions to these problems include use of a surface coating to provide a uniform emittance and use of shields or proper location of the control point on which the radiometer will be focused.

# VIII. PROBLEMS ENCOUNTERED

Weld quality and thermal patterns are extremely sensitive to small variations in welding techniques, heat input, and heat extraction, making complete and precise monitoring of all pertinent variables mandatory for quantitative assessment of the improvement in weld properties effected by cryogenic chilling. Temperature changes in the weldment are extremely rapid and thermal gradients in a small area are extraordinarily large, making accurate, instantaneous and continuous recording of temperature at multiple points in the weldment a necessity for precise determination of thermal patterns.

To meet these demands for monitoring welding parameters and temperature recording, a precision multiple channel recorder is required. Unless such a recorder is made available for use on this program, it will be necessary to extrapolate and interpolate critical data in such a manner that large errors could result.

Use of thermocouples for monitoring temperatures of a weldment for the purpose of controlling thermal patterns is not normally practical for production weldments. Preliminary investigations indicate that infrared radiometers would be suitable for this purpose as they do not require contact with the part being welded. If this study is to be continued so that a feed-back system for control of thermal patterns can be developed, approximately five radiometers will be required with sufficient man-hour allowance for future work to adapt their use to this program. In addition, a man-hour allowance will be required to compensate for hours already expended on the preliminary radiometer study, if the experimental work on the original program is to be completed.

Plate material stocks are now marginal, and in the event that unexpected difficulties are encountered in establishing optimum thermal patterns and/or if the work is extended to cover detailed development of front side cooling and an infrared control system, additional materials will be required.

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## APPENDIX I

### Isothermal Patterns and Time-Temperature Curves for Points along Weld Centerline

Figure 5 - 1/2" 2014-T6 Weld, Unchilled Thermal Pattern, Preliminary

Figure 6 - 1/2" 2014-T6 Weld, Chilled Thermal Pattern, Preliminary

Figure 7 - Effect of Liquid $CO_2$ Chilling on Time-Temperature Curves During Welding of 1/2" 2014-T6 Aluminum Plate

Figure 8 - 5/16" 2014-T6 Weld, Unchilled Thermal Pattern, Preliminary

Figure 9 - 5/16" 2014-T6 Weld, Chilled Thermal Pattern, Preliminary

Figure 10- Effect of Liquid $CO_2$ Chilling on Time-Temperature Curves During Welding of 5/16" 2014-T6 Aluminum Plate

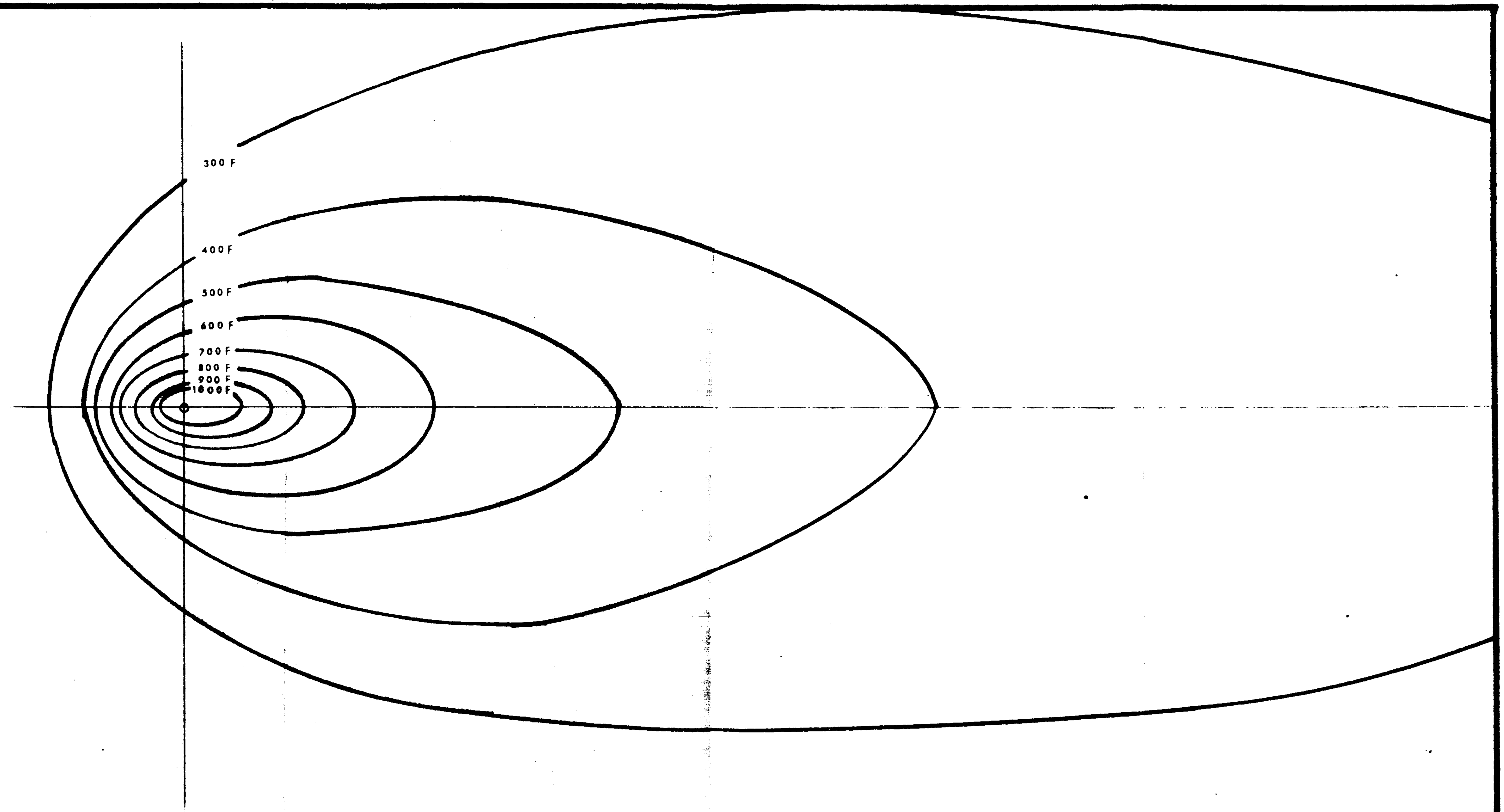



FIGURE 5 - THERMAL PATTERN FOR WELD PANEL IF2 NO CHILLING, 1/2" 2014-T6, PENETRATION PASS

THERMAL PATTERN

FULL SCALE

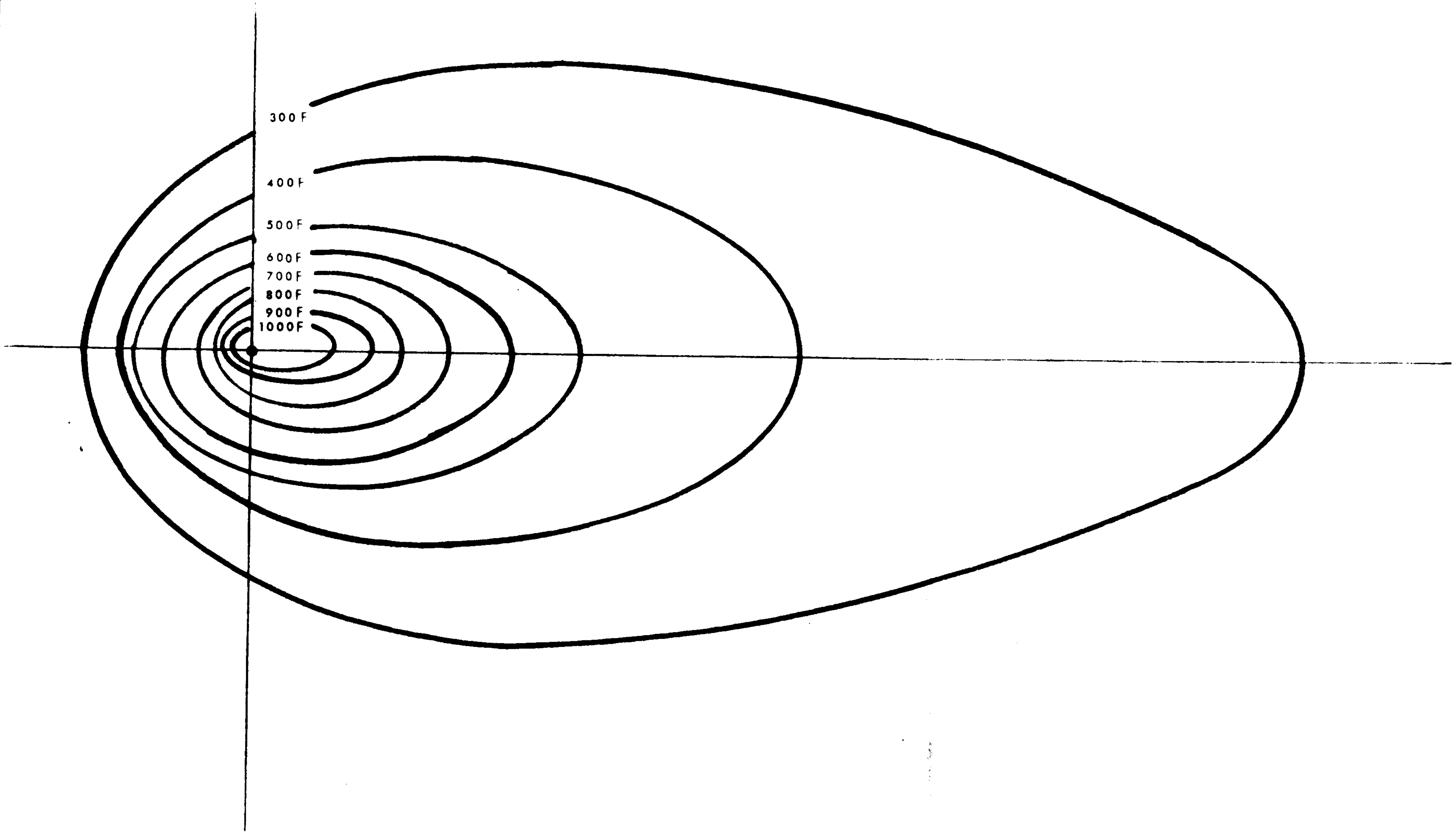



FIGURE 6 - THERMAL PATTERN FOR WELD PANEL IDC3 $CO_2$ CHILLED, 1/2" 2014-T6, PENETRATION PASS

THERMAL PATTERN

. ULL SCALE

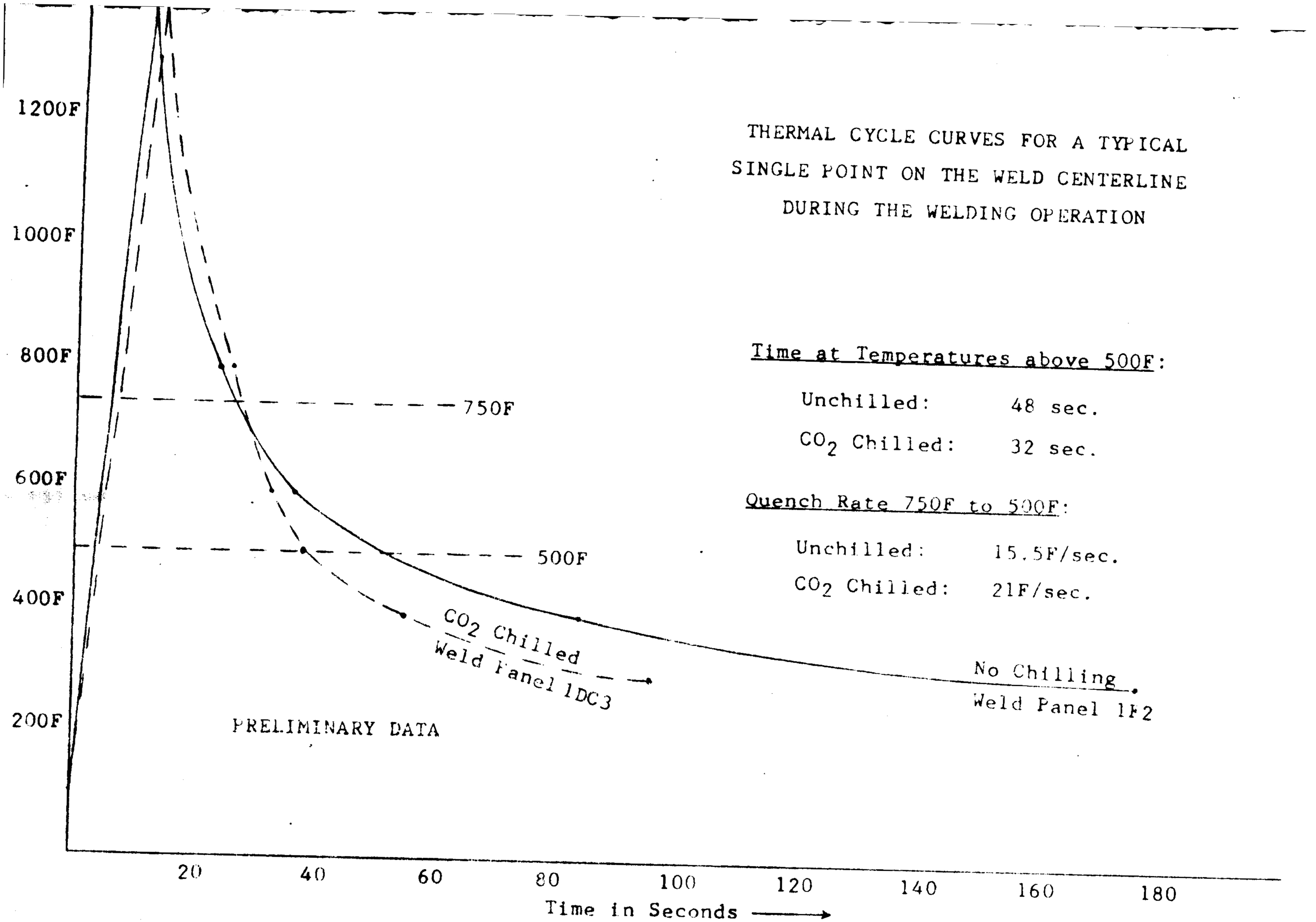



FIGURE 7 - EFFECT OF LIQUID $CO_2$ CHILLING ON TIME-TEMPERATURE CURVES DURING WELDING OF 1/2" 2014-T6 ALUMINUM PLATE

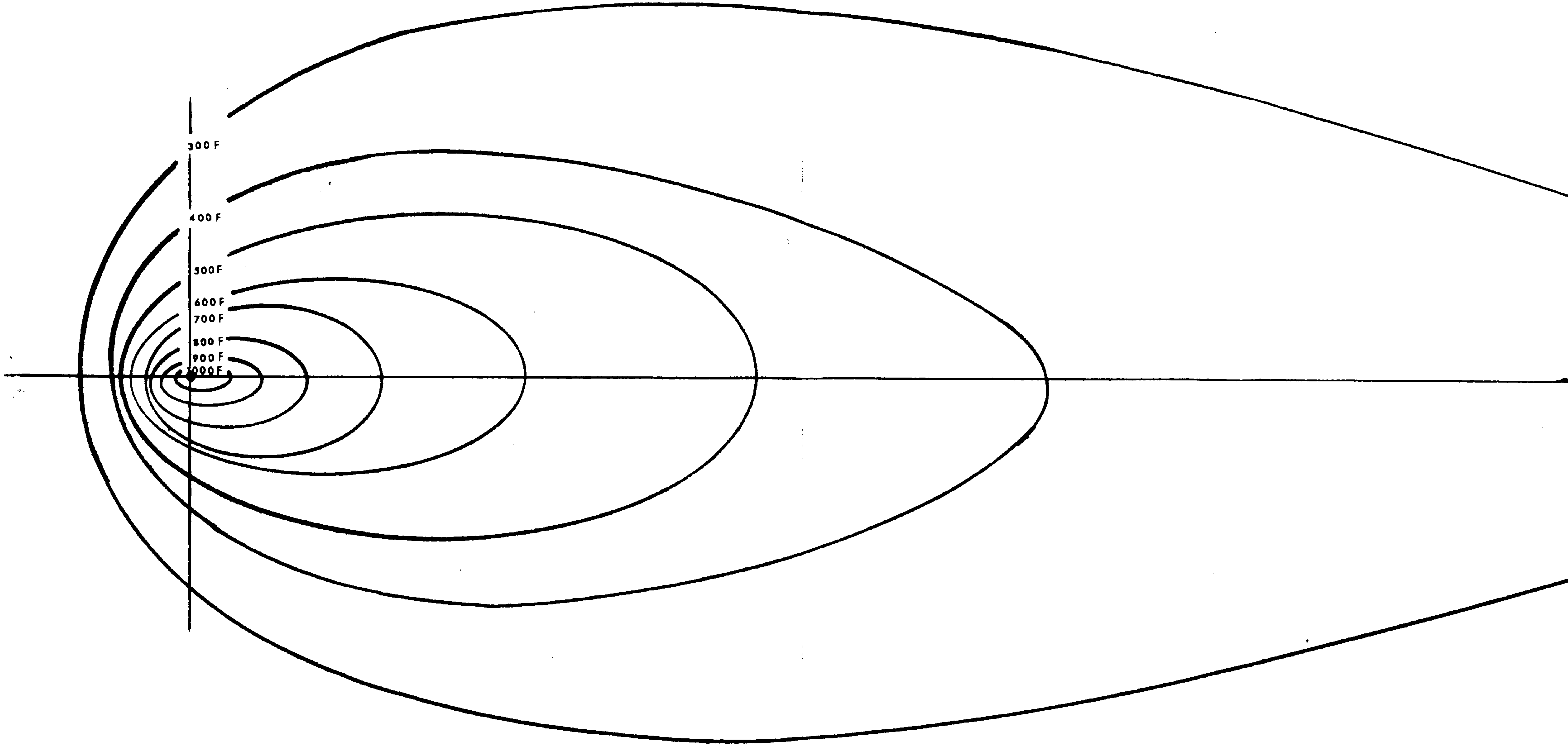



FIGURE 8 - THERMAL PATTERN FOR WELD PANEL 1A1 NO CHILLING, 5/16" 2014-T6, PENETRATION PASS.

THERMAL PATTERN

FULL SCALE

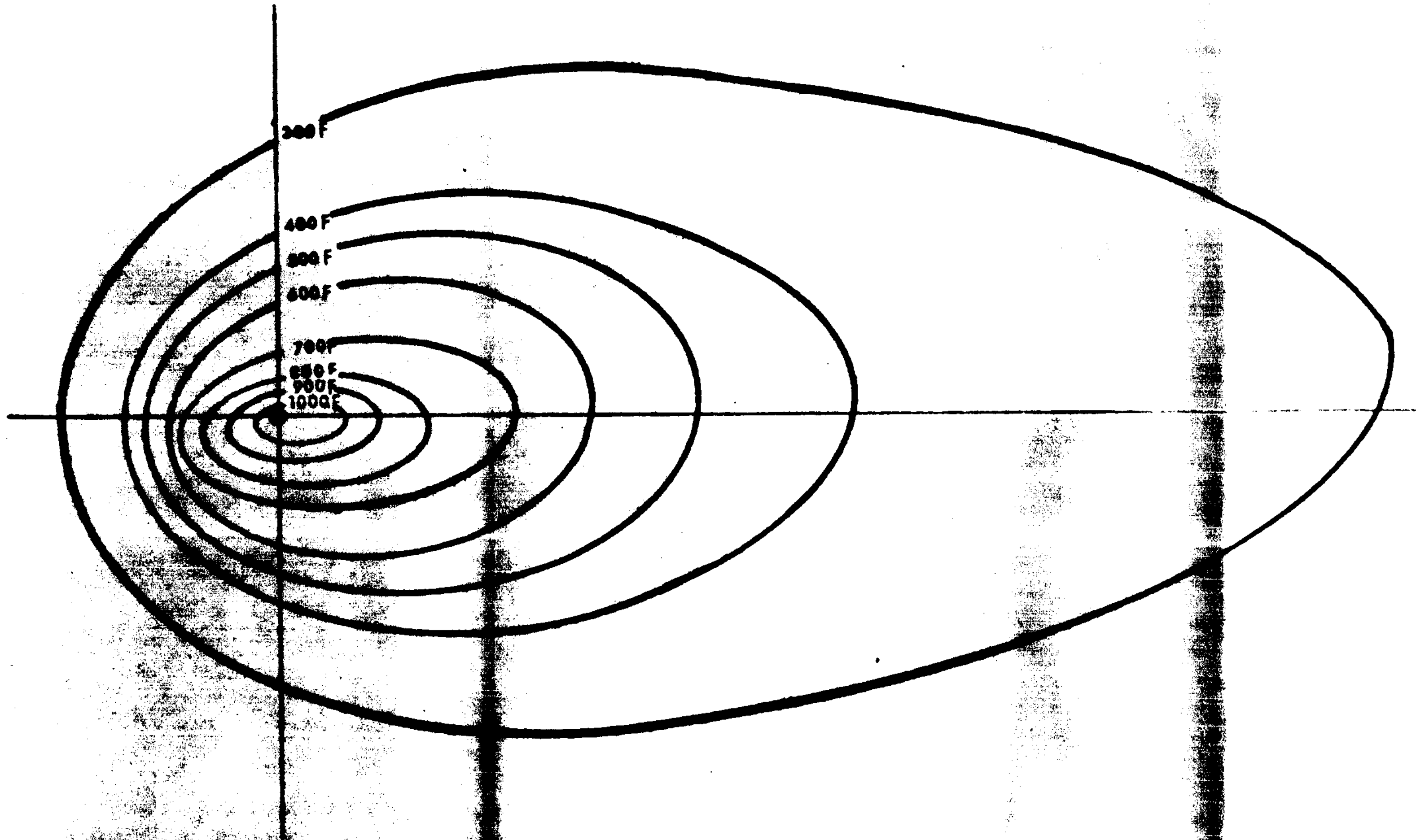



FIGURE 9. THERMAL PATTERN FOR WELD PANEL IECI $CO_2$ CHILLED, 5/16" 2014-T6 PENETRATION PASS.

THERMAL PATTERN

FULL SCALE

# APPENDIX II

## Time-Temperature Curves
(Current Work)

Figure 11 - $CO_2$ Chilled vs Unchilled (5/16" 2219-T87)

Figure 12 - Temperature vs Adjusted Time (5/16" 2219-T87)
3/8" from Weld Centerline - Cooled

Figure 13 - Temperature vs Adjusted Time (5/16" 2219-T87)
6/8" from Weld Centerline - Chilled

Figure 14 - Temperature vs Adjusted Time (5/16" 2219-T87)
1-1/4" from Weld Centerline - Chilled

Figure 15 - Adjusted Time-Temperature (5/16" 2219-T87)
Fusion Weld, 3/8" from Weld Centerline, Uncooled

Figure 16 - Adjusted Time-Temperature Data - No Cooling
(5/16" 2219-T87), 6/8" from Weld Centerline

Figure 17 - Adjusted Time-Temperature Data (5/16" 2219-T87)
1-1/4" from Centerline of Weld

Figure 18 - Time-Temperature Data - Cooled (1/2" 2219-T87)
3/8" from Weld Centerline

Figure 19 - Time-Temperature Data - Cooled (1/2" 2219-T87)
6/8" from Weld Centerline

Figure 20 - Time-Temperature Data - Cooled (1/2" 2219-T87)
1-1/4" from Weld Centerline

Figure 21 - Adjusted Time-Temperature Data - Cooled (1/2" 2219-T87), Fusion Weld, 3/8" from Weld Centerline

Figure 22 - Adjusted Time-Temperature Data - Cooled
(1/2" 2219-T87), 6/8" from Weld Centerline

Figure 23 - Adjusted Time-Temperature Data - Cooled
(1/2" 2219-T87), 1-1/4" from Weld Centerline

TIME - TEMPERATURE DATA

$CO_2$ CHILLED VS UNCHILLED
5/16" 2219-T87 - 6/8" FROM WELD ℄

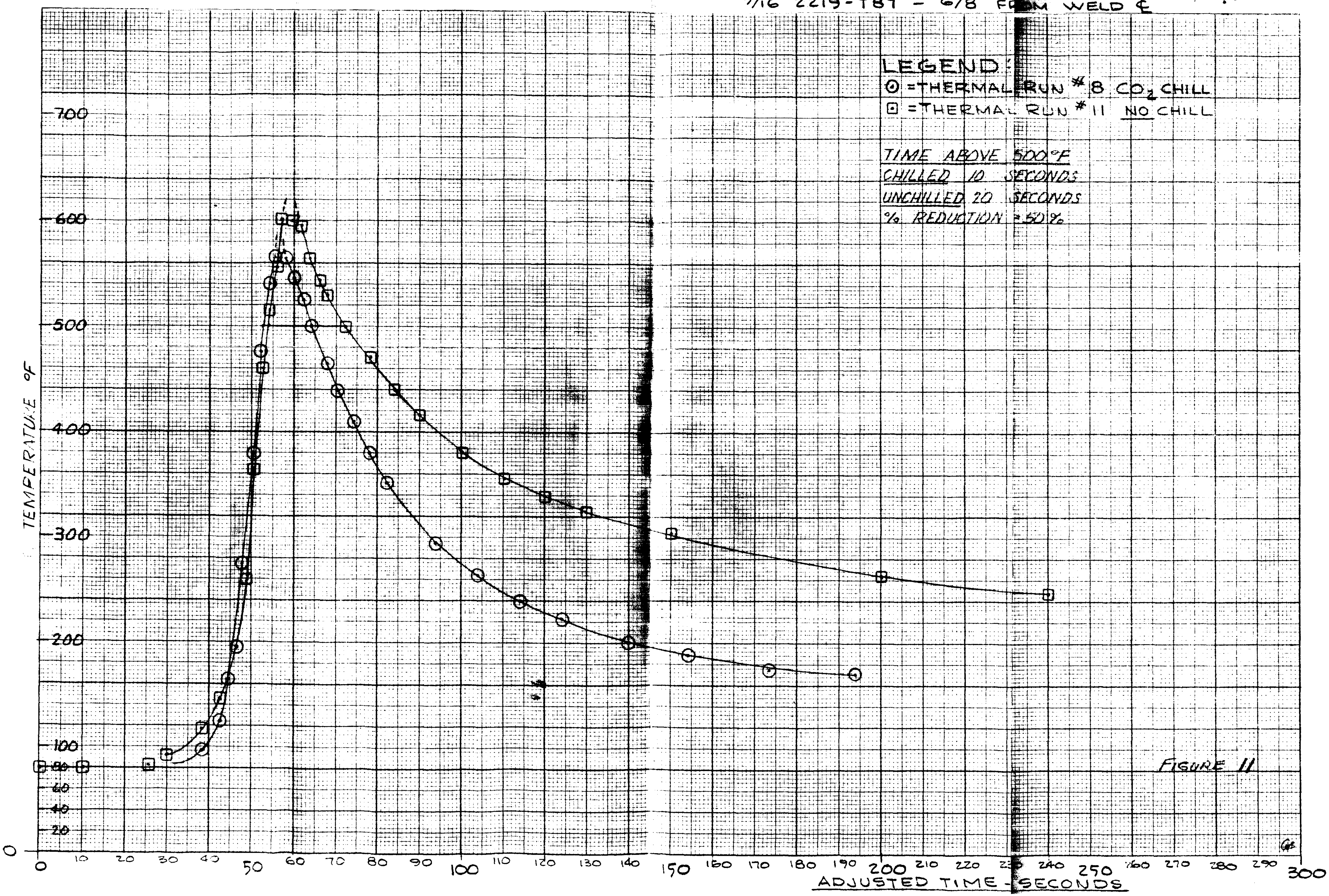



FIGURE 11

TEMPERATURE VS. ADJUSTED TIME
THERMOCOUPLE READINGS.

RUN 2AC-1 $CO_2$ COOLED: 2-.024" Ø JETS
5/16" 2219-T87 — 3/8" FROM WELD ℄

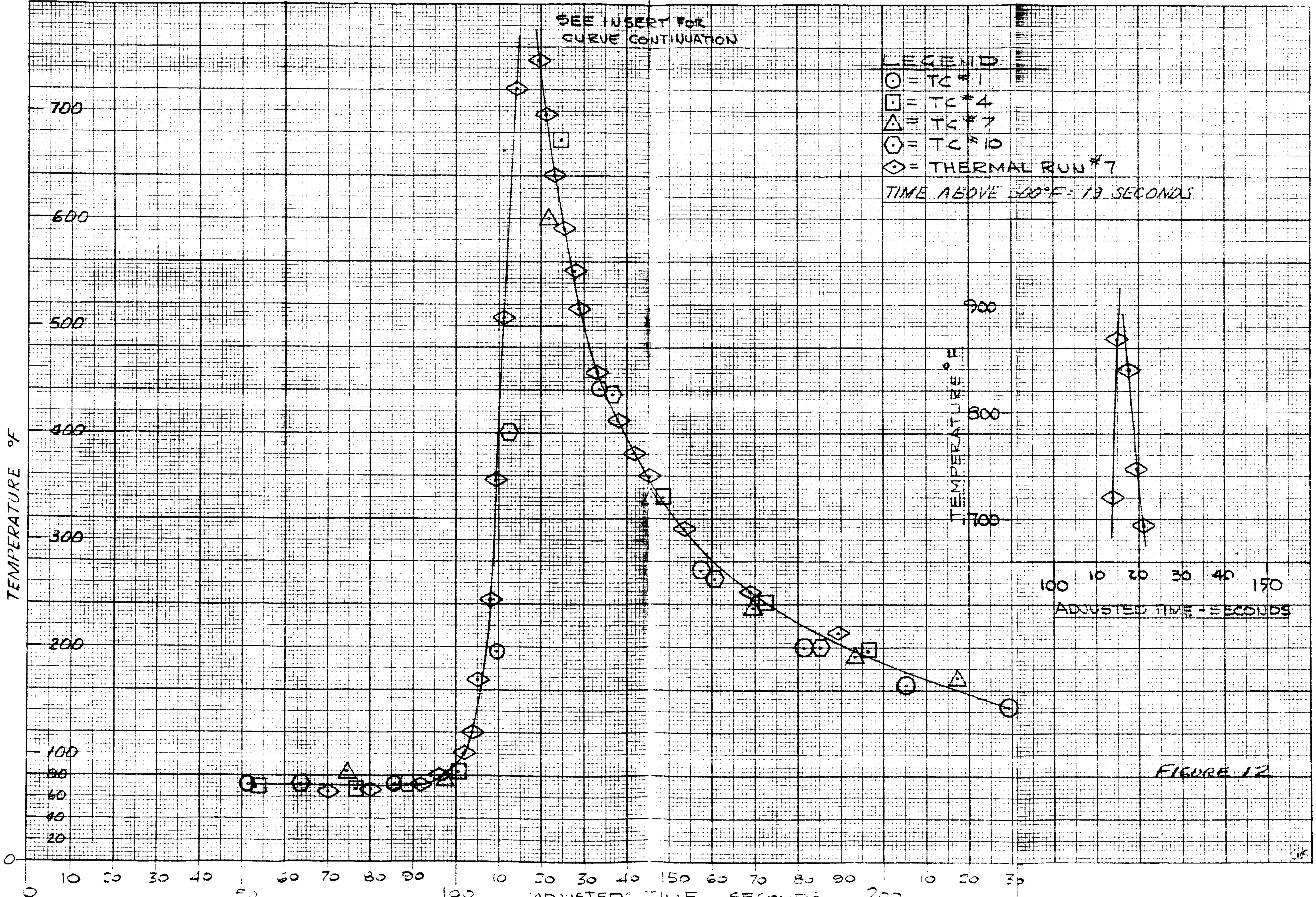
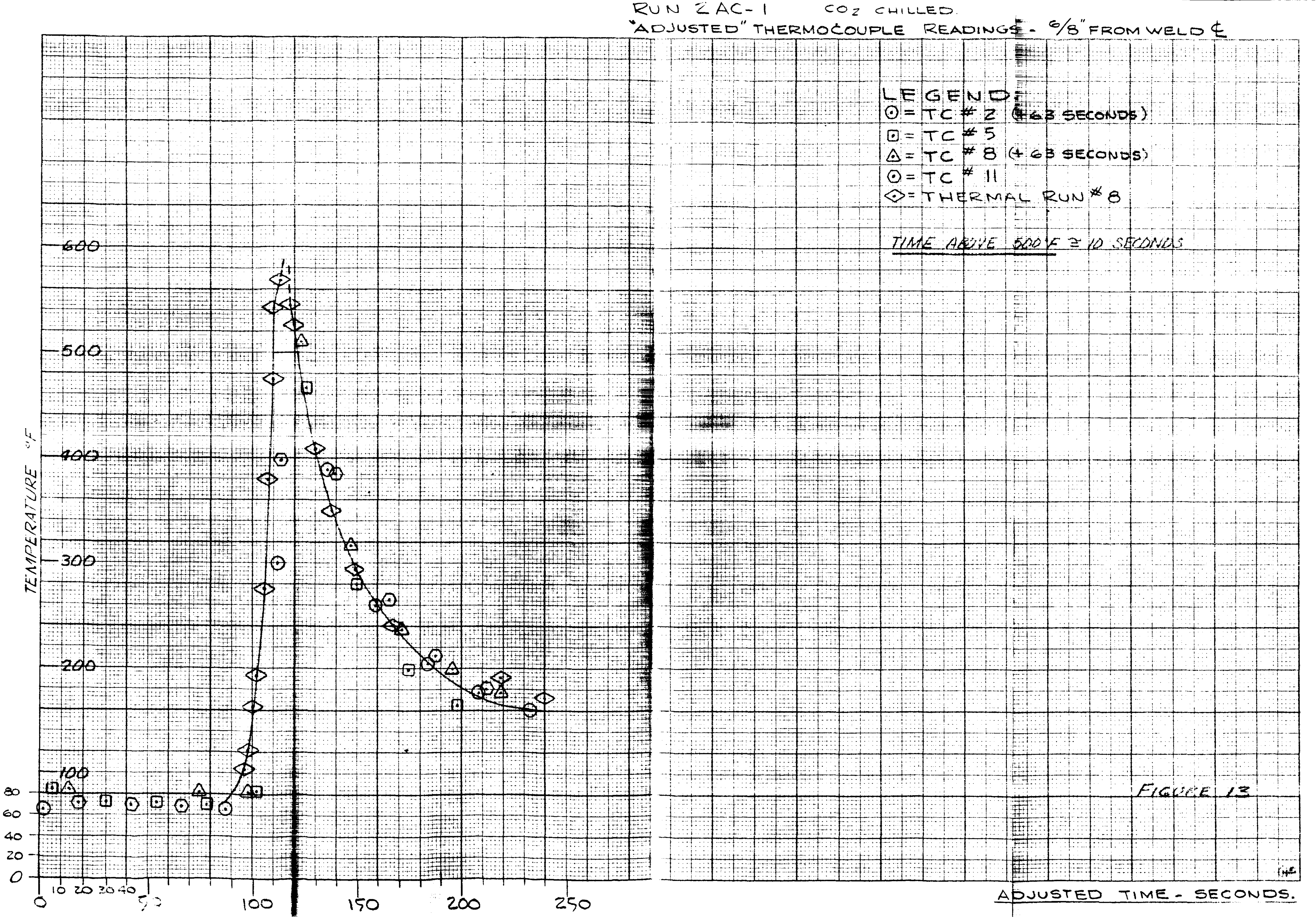
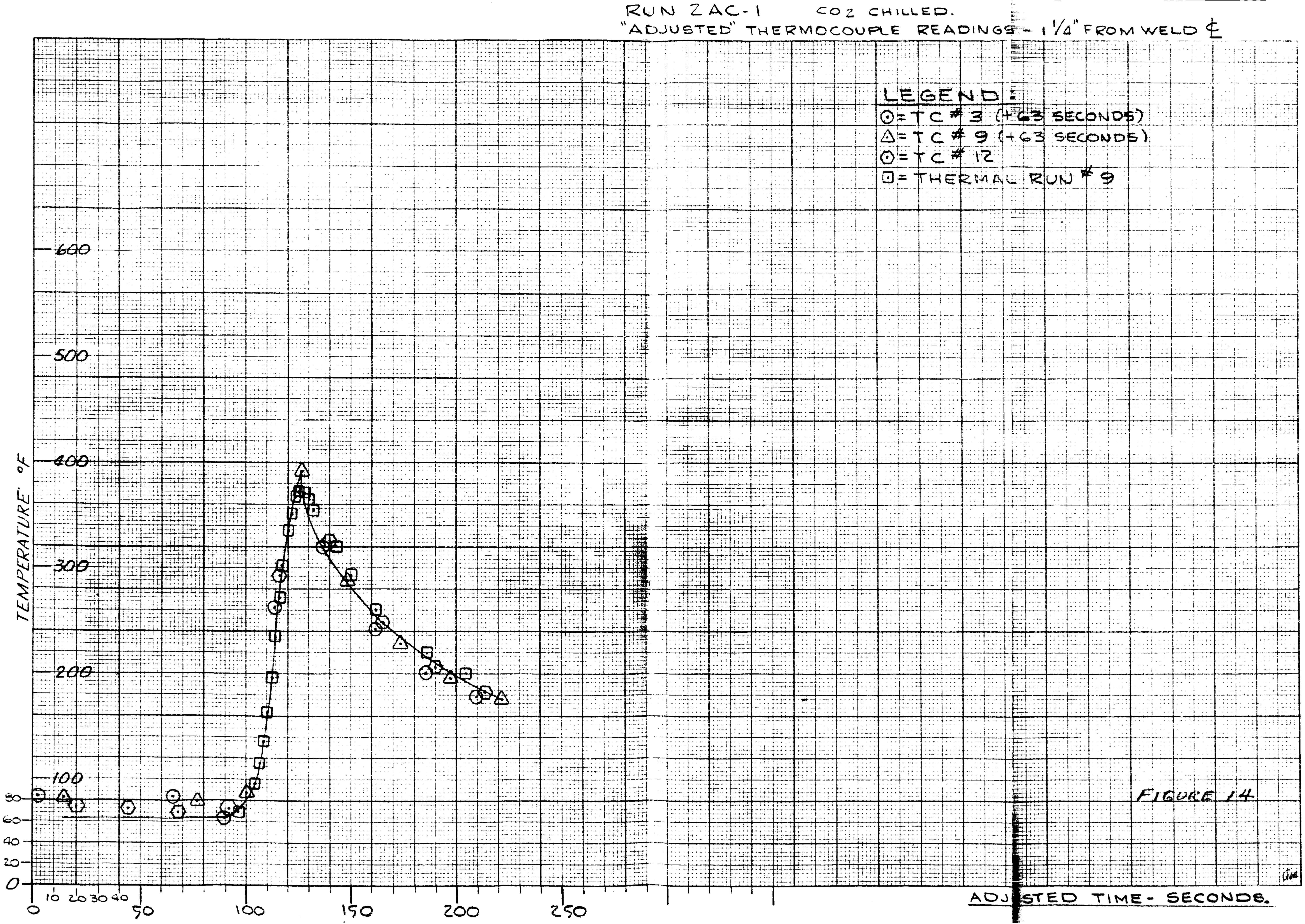



FIGURE 12


RUN 2AC-1 $CO_2$ CHILLED
"ADJUSTED" THERMOCOUPLE READINGS - 5/8" FROM WELD ℄
LEGEND:
⊙ = TC # 2 (+63 SECONDS)
⊡ = TC # 5
△ = TC # 8 (+63 SECONDS)
⊙ = TC # 11
◇ = THERMAL RUN # 8
TIME ABOVE 500°F ≅ 10 SECONDS
TEMPERATURE °F
600
500
400
300
200
100
80
60
40
20
0
0
10
20
30
40
50
100
150
200
250
ADJUSTED TIME - SECONDS.
FIGURE 13



RUN 2AC-1 CO2 CHILLED.
"ADJUSTED" THERMOCOUPLE READINGS - 1 1/4" FROM WELD ℄
LEGEND:
⊙ = TC # 3 (+63 SECONDS)
△ = TC # 9 (+63 SECONDS)
⊙ = TC # 12
⊡ = THERMAL RUN # 9
TEMPERATURE °F
0
20
40
60
80
100
200
300
400
500
600
0
10
20
30
40
50
100
150
200
250
ADJUSTED TIME - SECONDS.


FIGURE 14

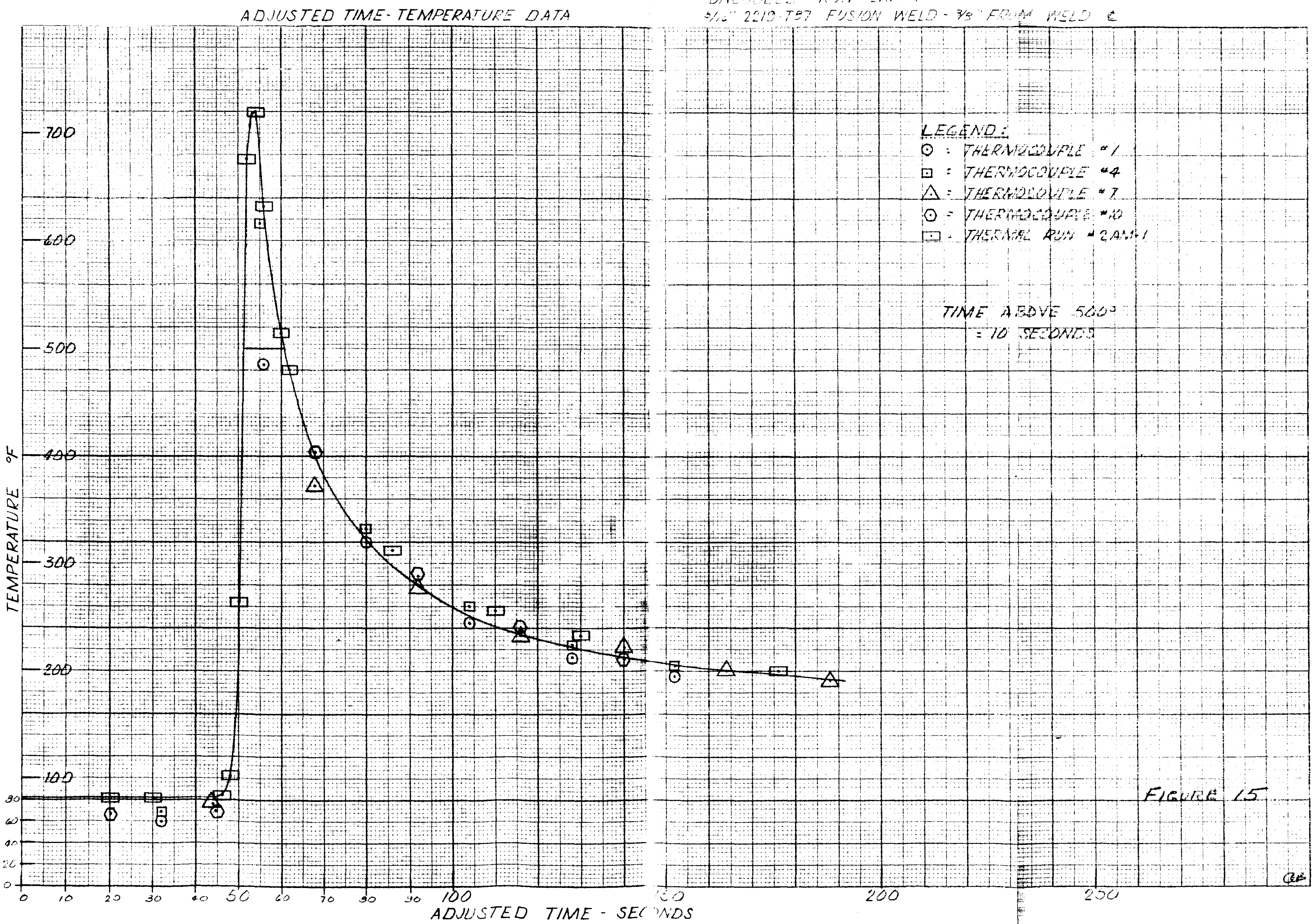

ADJUSTED TIME-TEMPERATURE DATA
UNCOOLED - RUN 2AM-1
5/16" 2219-T87 FUSION WELD - 3/8" FROM WELD ℄
LEGEND:
⊙ : THERMOCOUPLE #1
⊡ : THERMOCOUPLE #4
△ : THERMOCOUPLE #7
⬡ : THERMOCOUPLE #10
⊡ : THERMAL RUN #2AM-1
TIME ABOVE 500° = 10 SECONDS
TEMPERATURE °F
ADJUSTED TIME - SECONDS
0
20
40
60
80
100
200
300
400
500
600
700
10
30
50
70
90
150
250

FIGURE 15

ADJUSTED TIME - TEMPERATURE DATA - NO COOLING

RUN 2 AM-1
5/16" 2219-T87 from weld ℄

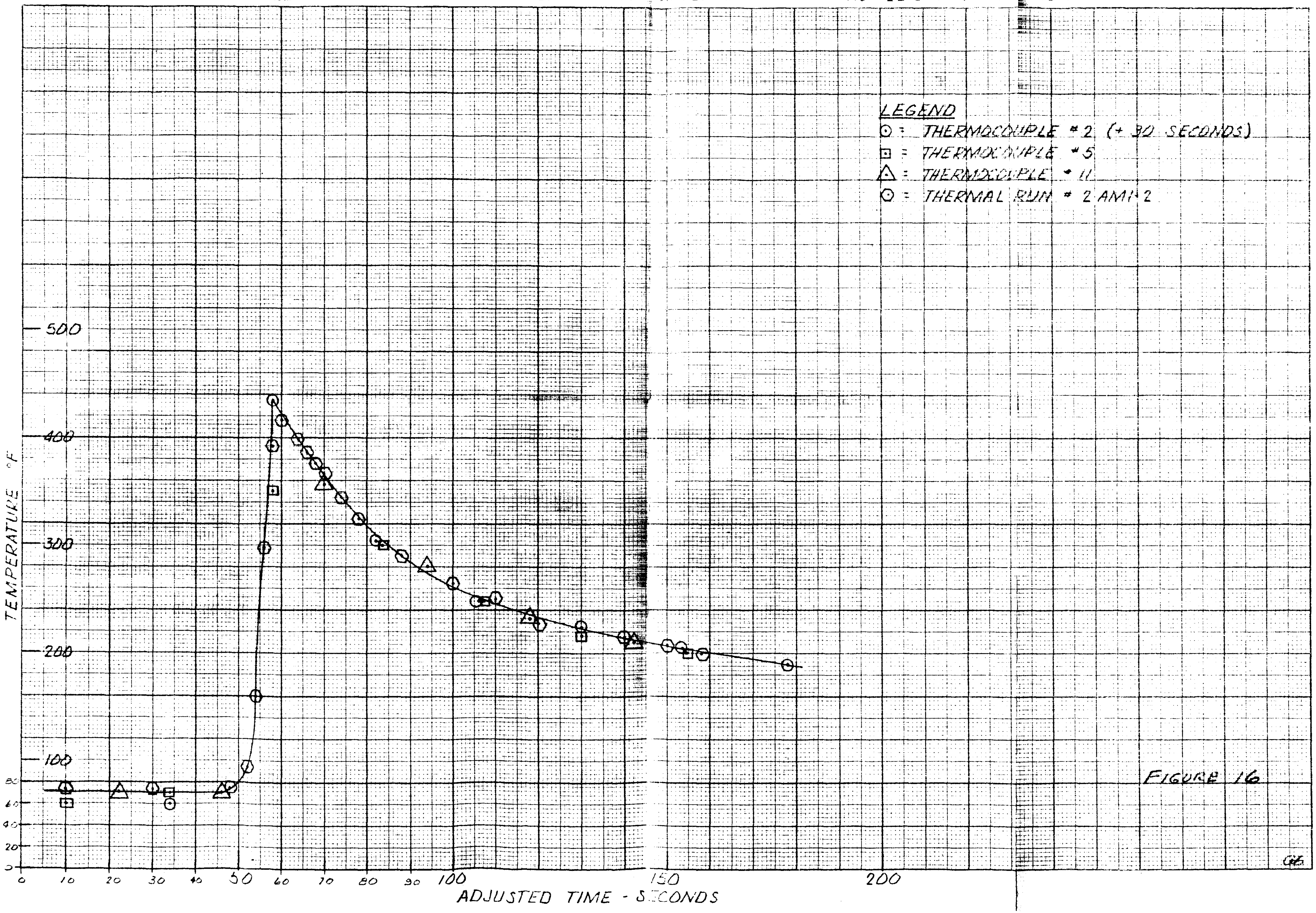



FIGURE 16

RUN 2AM-1
5/16" 2219-T87 1 1/4" FROM WELD ℄

ADJUSTED TIME - TEMPERATURE DATA

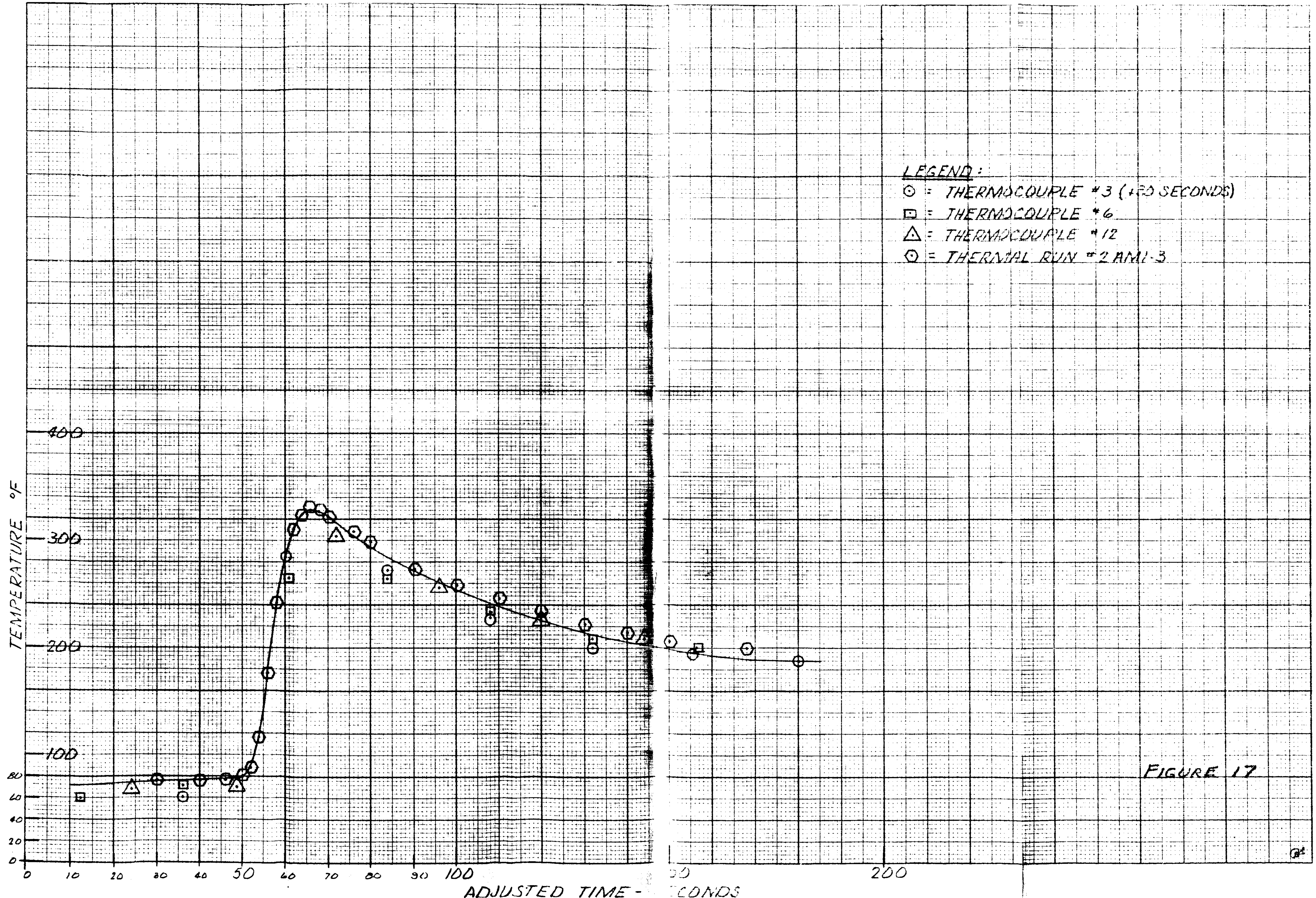
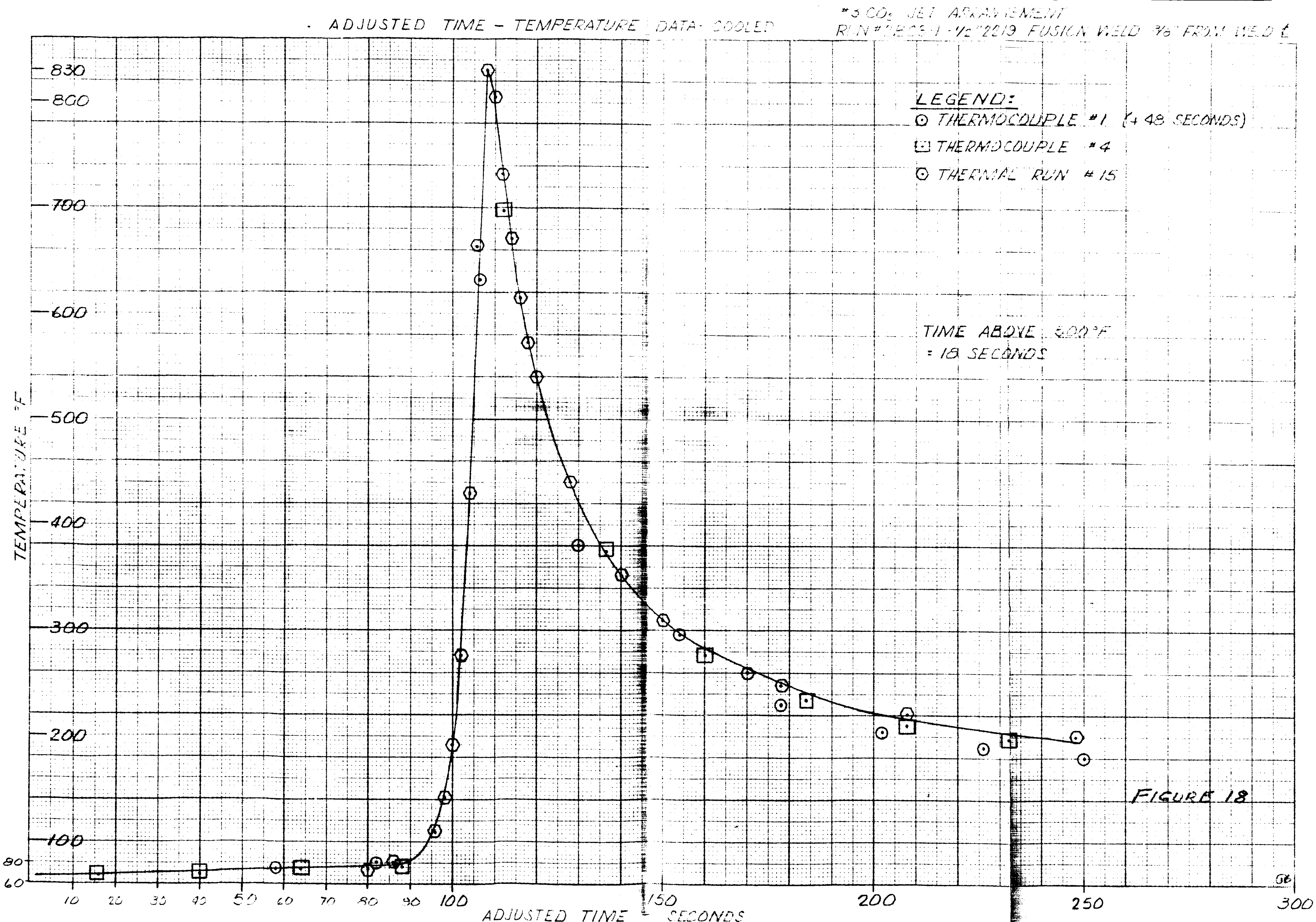



FIGURE 17



ADJUSTED TIME - TEMPERATURE DATA - COOLED
#3 $CO_2$ JET ARRANGEMENT
RUN #[illegible] - 1/2" 2219 FUSION WELD 3/8" FROM WELD ℄
LEGEND:
THERMOCOUPLE #1 (+48 SECONDS)
THERMOCOUPLE #4
THERMAL RUN #15
TIME ABOVE 500°F
= 18 SECONDS
TEMPERATURE °F
ADJUSTED TIME SECONDS
830
800
700
600
500
400
300
200
100
80
60
10
20
30
40
50
60
70
80
90
100
150
200
250
300


FIGURE 18

ADJUSTED TIME - TEMPERATURE DATA - COOLED

#3 $CO_2$ JET ARRANGEMENT
RUN 2BC3-1-½" 2219 FUSION WELD - 4/8" FROM WELD ℄

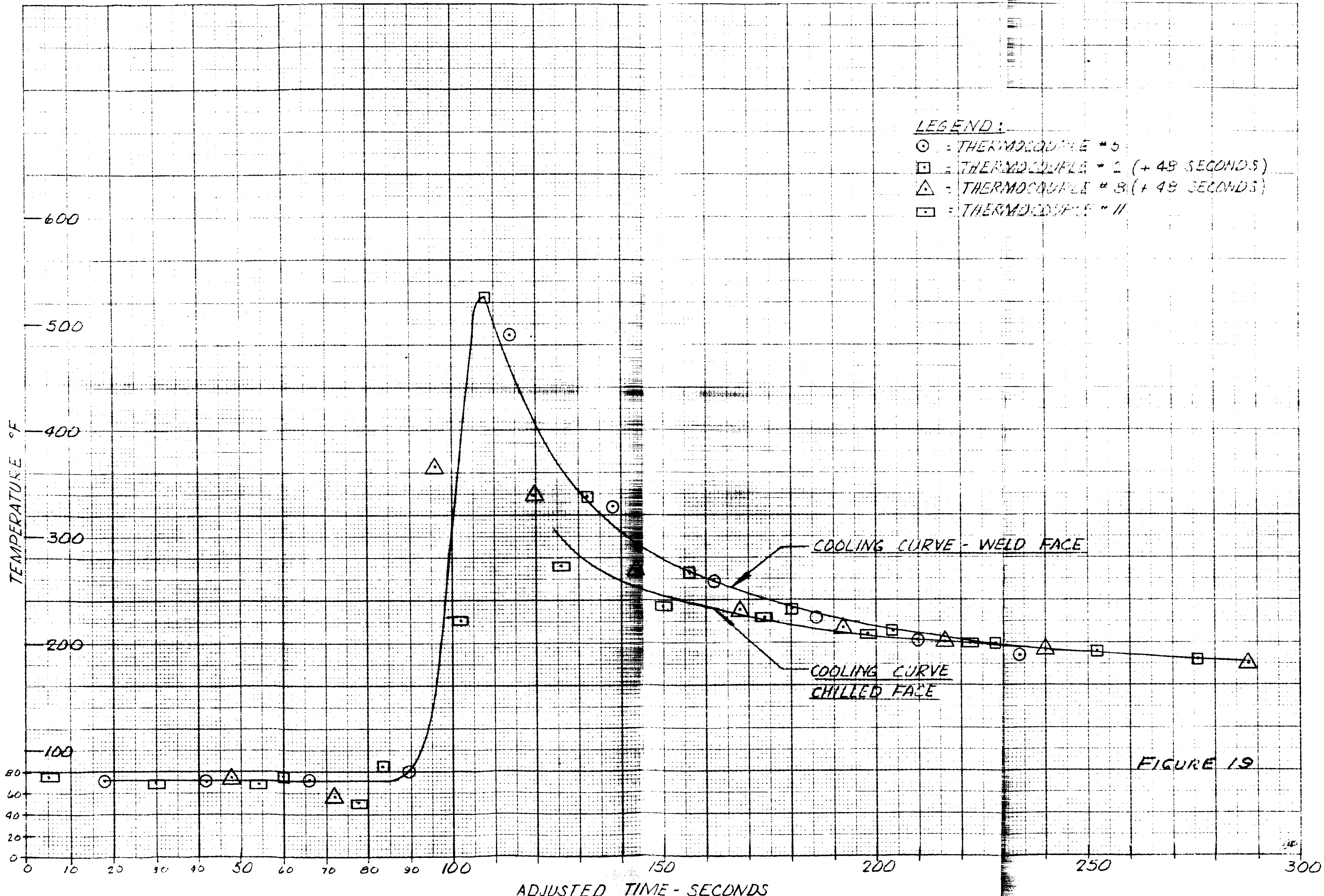
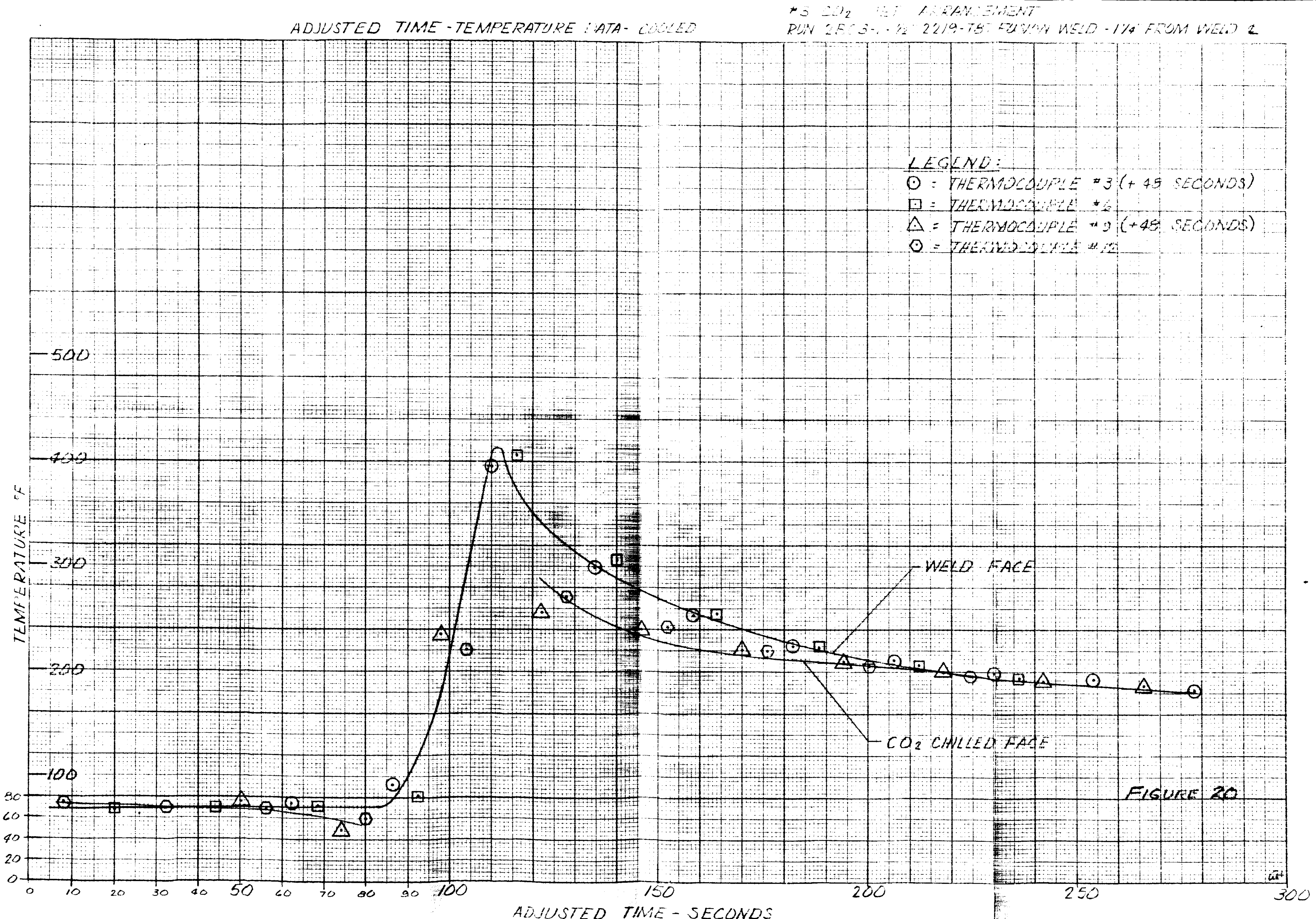



FIGURE 19



ADJUSTED TIME-TEMPERATURE DATA- COOLED
RUN 25 3- - 1/2" 2219-T8 FUSION WELD - 1/4" FROM WELD ℄
LEGEND:
⊙ = THERMOCOUPLE #3 (+45 SECONDS)
⊡ = THERMOCOUPLE #6
△ = THERMOCOUPLE #9 (+48 SECONDS)
⊙ = THERMOCOUPLE #12
WELD FACE
$CO_2$ CHILLED FACE
TEMPERATURE °F
500
400
300
200
100
80
60
40
20
0
ADJUSTED TIME - SECONDS
0
10
20
30
40
50
60
70
80
90
100
150
200
250
300


FIGURE 20

TIME-TEMPERATURE DATA - COOLED

#3 $CO_2$ JET ARRANGEMENT
1/2"-2213 T87 - 3/8 FROM WELD ℄

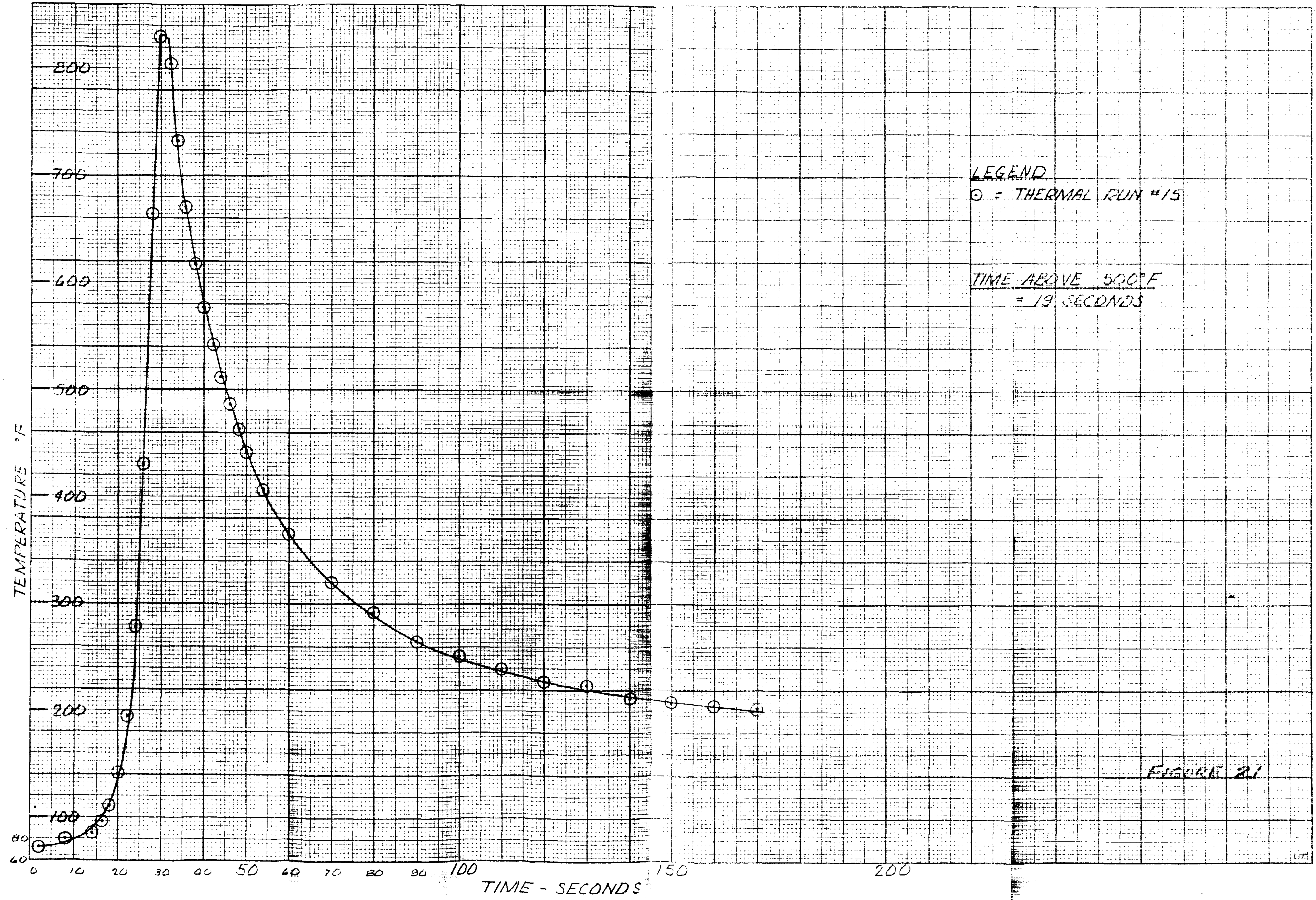



FIGURE 21

TIME - TEMPERATURE DATA - COOLED

#3 $CO_2$ 1ST ARRANGEMENT
Y2-2219-1ST - 4/8' FROM WELD 2

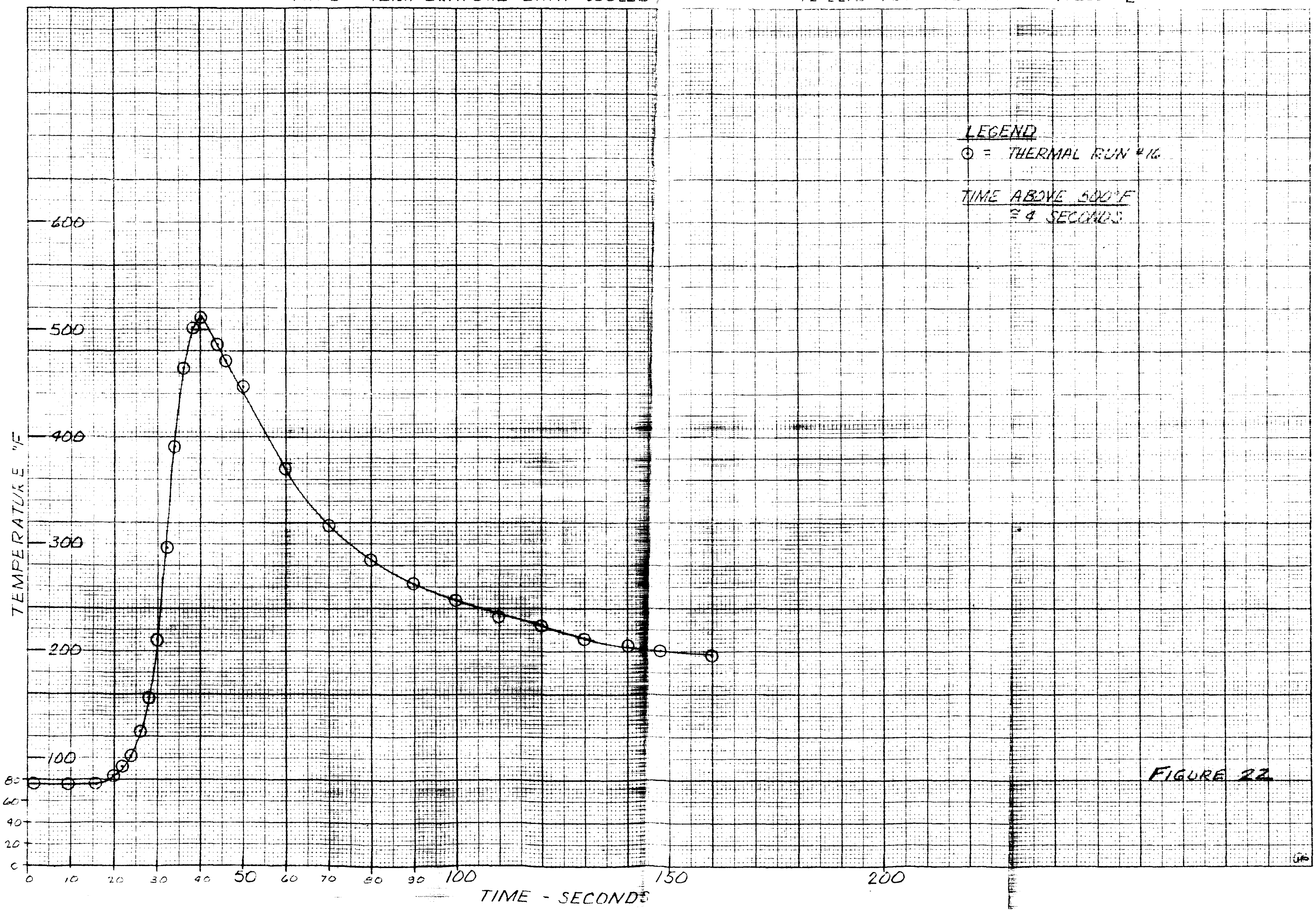



FIGURE 22

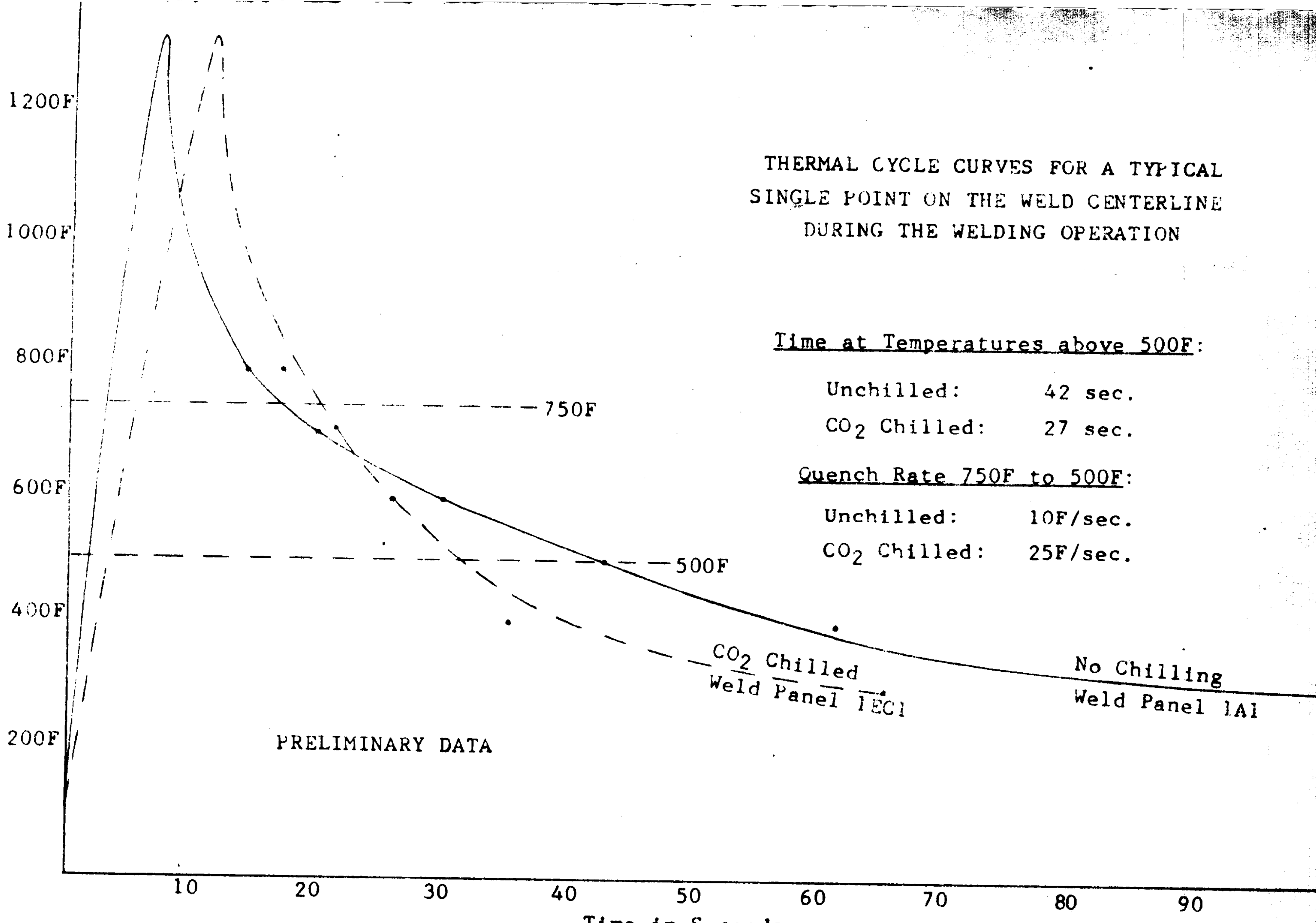



FIGURE 10 - EFFECT OF LIQUID $CO_2$ CHILLING ON TIME-TEMPERATURE CURVES DURING WELDING OF 5/16" 2014-T6 ALUMINUM PLATE

TIME - TEMPERATURE DATA - COOLED

#3 $CO_2$ JET ARRANGEMENT
1/2" - 2219 - T87 - 1 1/4" FROM WELD ℄

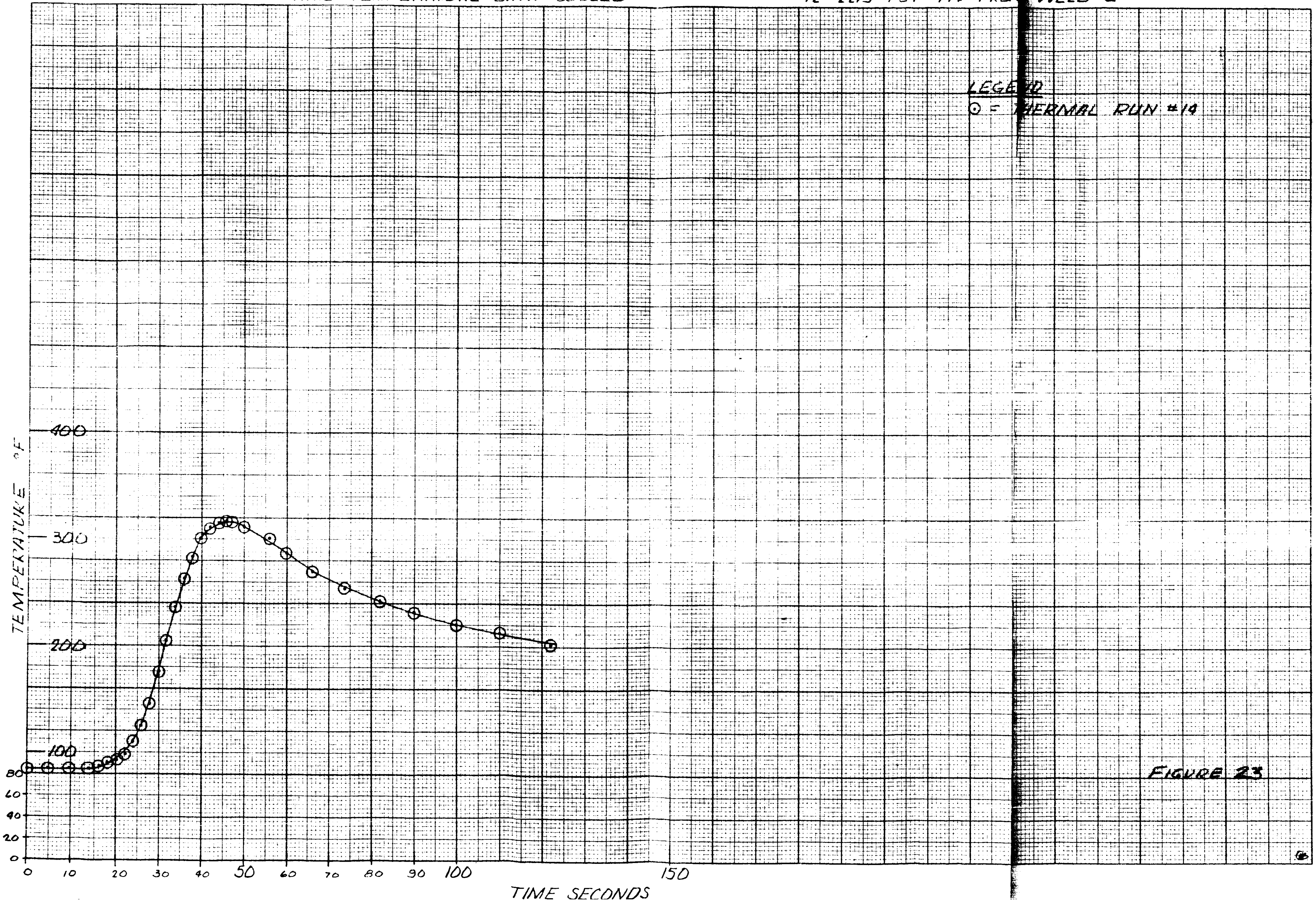



FIGURE 23